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DEPARTMENT OF TRANSPORTATION
DIVISION OF NEW TECHNOLOGY,
MATERIALS AND RESEARCH

OFFICE OF TRANSPORTATION MATERIALS AND RESEARCH

VEHICLE CRASH TESTS OF A MOVABLE CONCRETE BARRIER

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16. Abstract

A movable concrete barrier (MCB) has been developed to address the need for a positive barrier for separating traffic in a reversible lane. Crash tests were conducted to qualify this MCB for highway use. Demonstrations of a transfer vehicle to move the MCB were also performed and evaluated. The test barrier was designed and built by Barrier Systems, Incorporated, based on an Australian patent. Six crash tests were conducted using two barrier cross sections and two types of hinge connections between barrier segments. Two unsuccessful tests on the first type of barrier led to cross section and hinge connection modifications. The new, more heavily reinforced MCB and hinge connection performed well through the four following tests. These crash tests involved two large cars, 4370 and 4300 lb, (1982 and 1950 kg), travelling 59.3 and 59.4 mph (26.5 and 26.6 m/s) and impacting at 24° and 16°, respectively. The other two tests involved two small cars weighing 2000 and 1890 lb, (907 and 857 kg), travelling 57.7 and 58.6 mph (25.8 and 26.2 m/s) and impacting at 15 1/2° and 20 1/2°, respectively. It was concluded that the crash tests satisfied the requirements for structural adequacy and occupant risk and partially satisfied the vehicle trajectory requirements of NCHRP Report 230. Transfer vehicle demonstrations included moving the MCB one full-lane width, straightening a deflected barrier, and transporting, assembling and transferring the MCB on a 1400-foot (427 m) radius curve with 12% cross slope and on a 5% longitudinal grade.

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CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40	millimetres (mm)
		.02540	metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2)	.09290	square metres (m^2)
	acres	.4047	hectares (ha)
Volume	gallons (gal)	3.785	litre (l)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s	28.317	litres per second l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph)	.4470	metres per second (m/s)
	feet per second (fps)	.3048	metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G) (ft/s^2)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs)	4.448	newtons (N)
	(1000 lbs) kips	4448	newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb)	1.356	joules (J)
	foot-kips (ft-k)	1356	joules (J)
Bending Moment or Torque	inch-pounds (in-lbs)	.1130	newton-metres (Nm)
	foot-pounds (ft-lbs)	1.356	newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch (ksi$\sqrt{in}$)	1.0988	mega pascals$\sqrt{metre}$ (MPa $\overline{m}$)
	pounds per square inch square root inch (psi$\sqrt{in}$)	1.0988	kilo pascals$\sqrt{metre}$ (KPa $\overline{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{+F - 32}{1.8} = +C$	degrees celsius (°C)
Concentration	parts per million (ppm)	1	milligrams per kilogram (mg/kg)

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1. INTRODUCTION

1.1 PROBLEM

Traffic congestion has increased rapidly in recent years. At many highway and bridge locations there has not been room to add lanes and/or there have been insufficient funds. At such locations where traffic is heavy in one direction in the morning and heavy in the opposite direction in the evening, a need has developed for a median barrier that can be moved easily from one lane boundary to another. A movable median barrier is needed to adjust the number of lanes available to peak traffic while maintaining a positive barrier between opposing lanes of traffic. Over the past 10 years, several systems have been proposed to California Department of Transportation (Caltrans). These systems either required an extensive and complicated mechanical installation within the roadbed or demonstrated inferior performance as a barrier. Caltrans presently has a pressing need for a movable median barrier on the Coronado Bridge in San Diego. The relocatable pylons currently used do nothing to retain out-of-control vehicles, and there have been severe head-on collisions (1)*. There are other locations where a movable barrier could be used to advantage. These include locations where a permanent system is needed, and also construction and maintenance locations where a mobile barrier is needed that will provide greater protection to motorists and workers.

1.2 OBJECTIVE

Standard vehicle crash tests were to be conducted to qualify a movable concrete barrier for highway use. The operation of the barrier transfer vehicle was to be demonstrated and evaluated.

1.3 BACKGROUND

Several proposals for movable median barriers have been submitted to Caltrans. Most have been impractical for one reason or another. One scheme involved the use of overhead structures with lifting hooks on trolleys to move the

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*Numbers in parenthesis and underlined refer to a reference list at the end of this report.

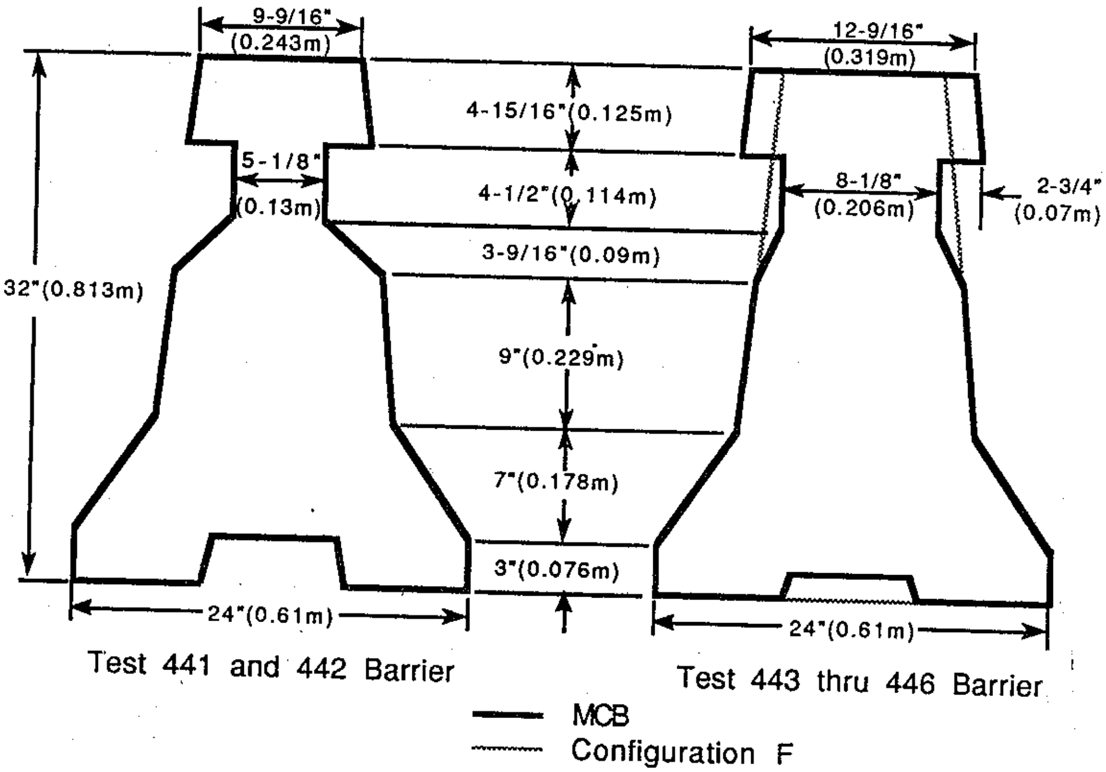
barrier. Some schemes required that rails or tracks be inserted into the pavement. This was particularly undesirable on bridge decks where reinforcing steel would be cut, thus weakening the structure. Pop-up barrier designs had inadequate strength and/or geometry to redirect impacting vehicles properly.

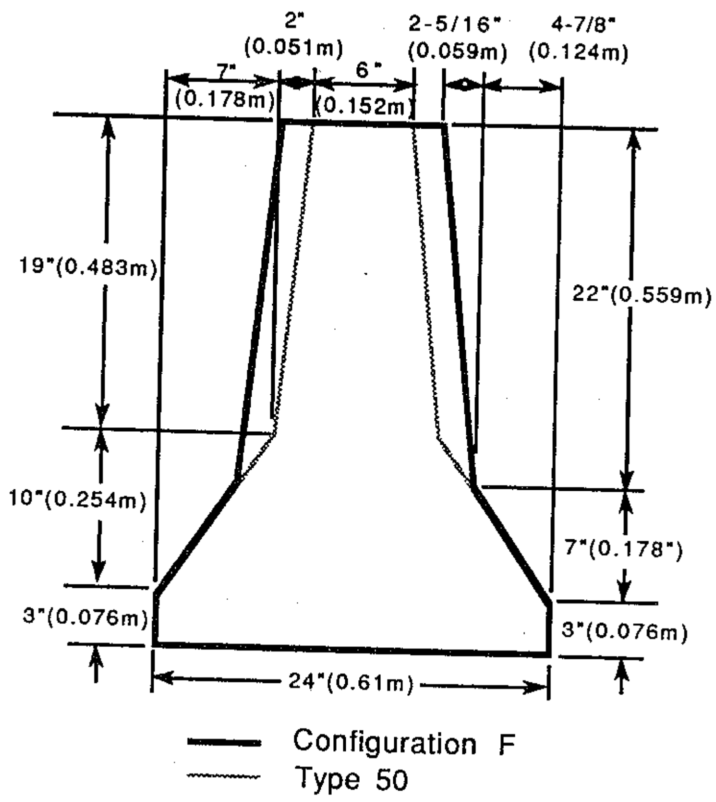
Some barrier designs included pulleys, motors and other electromechanical equipment installed on the roadway that would need periodic maintenance (a problem on busy freeways) and could cause grave traffic problems if not almost totally reliable and foolproof. A movable steel pipe barrier required a mechanical system of cables, pulleys and motors. This system included components under the roadway, was vulnerable to fouling by roadway debris, and had no guarantee of full system reliability. In addition, the pipe shape was particularly unsuitable for use as a vehicle barrier. The above proposals all had initial and/or maintenance costs that were quite high.

A promising new movable barrier design has been developed. This barrier was conceived, developed and tested in response to a continuing demand from the United States and other countries. The Quickchange Movable Concrete Barrier System was invented by Quick-Steel Engineering Pty, Ltd., of Botany, New South Wales, Australia. Barrier Systems, Incorporated of Sausalito, California is the North American licensee for the system. Hereafter this system will be referred to as a movable concrete barrier (MCB).

The MCB is a segmented concrete barrier that can be manufactured to any of the "New Jersey" type barrier shapes. Prototypes of the barrier have been made in both the California Type 50 (which uses a New Jersey profile) and the Configuration F shapes (Figure 1). The segments are 3.28 feet (1.0 m) in length, two feet wide (0.6 m) at the base, and 32 inches (0.8 m) high. They are joined by a pin and link hinge. At least three different designs of segment connection hardware were tested in Australia. The designs provided different amounts of rigidity at the vertical joints between segments. The most rigid joint condition was produced by the use of a steel channel 6.0 feet (1.85 m) long, set in a longitudinal keyway in the underside of the barrier segments, completely under one segment and halfway under the segments on each side (Figure 2). This channel dropped down below the bottom of the barrier segments when they were lifted up and moved laterally, allowing joint rotation, but remained

FIGURE 1
Configuration F, Type 50, and Movable Concrete Barrier Profiles





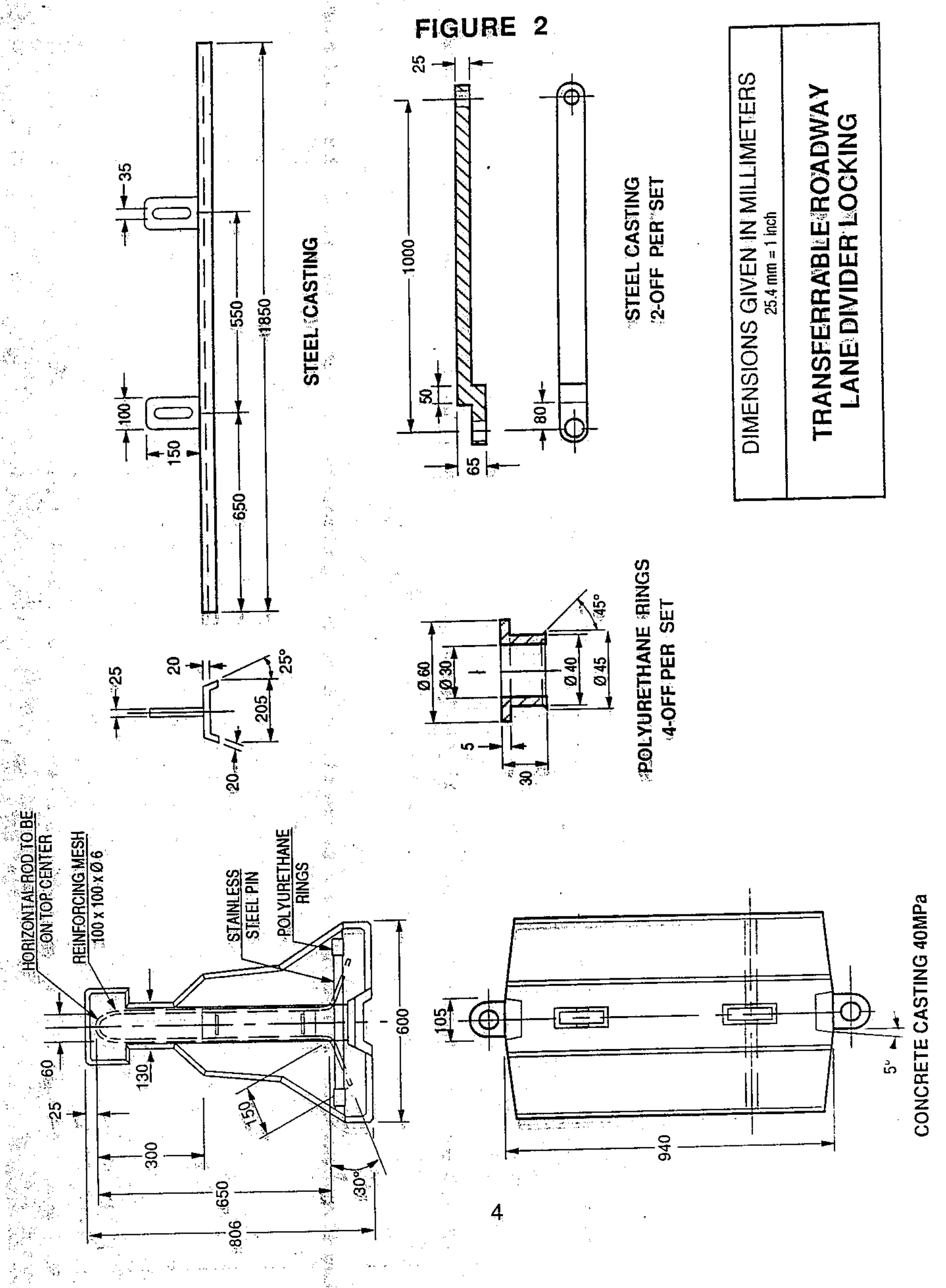


FIGURE 2. RIGID MCB WITH LOCKING CHANNEL - AUSTRALIAN DESIGN

suspended from the segments so it would not drop off as they were lifted. When the barrier segments were set back on the pavement, they automatically settled down over the locking steel channels. Thus, when the barrier segments were in position with all steel channels in the keyways, they formed a "rigid" barrier of any length. This "rigid" system was the one proposed for use in a permanent proposed for use in a permanent barrier installation. The "loose" system had a pin and link hinged joint without the bottom locking channel. It was proposed for temporary use at construction and maintenance sites (Figure 3). The base of the barrier had a polyurethane surface bonded to it. This surface was intended to increase frictional resistance to lateral movement of the barrier on the pavement. The barrier segments were freestanding on the highway pavement, i.e., there was no connection to the pavement.

The MCB is moved from one traffic lane line to another with a transfer vehicle system (Figure 4). The vehicle has an S-shaped conveyor assembly mounted on a mobile steel framework which may be either self-propelled or towed by a tractor. Closely spaced urethane conveyor wheels ride under the top lip on each side of the barrier stem. The wheels lift the segments a few inches off the pavement and the barrier segments are guided along the S-shaped conveyor to the new lane position, then lowered back down to the pavement. The barrier segments remain pinned together during the transfer operation. As the system moves forward, the barrier is transferred from left to right (when used as a median barrier). This minimizes the exposure of the transfer vehicle to traffic in both directions (Figure 5). Approximately 12 transfer tests were performed in Australia on a straight length of barrier at varying speeds on February 27, 1984. At 10 mph (4.5 m/s) the transfer was smooth and efficient (2). Earlier transfer tests were videotaped and shown to Caltrans engineers. These trial runs looked quite smooth.

On February 27-28, 1984, a series of 17 crash tests was conducted in Australia (2) by the Quick-Steel Company and BSI. Two test vehicles were used: 3,000 and 4,400 lb (1361 and 1996 kg). The impact angles were 7.5 degrees and 15 degrees and the speed varied between 25 and 55 mph (11.2 and 24.6 m/s). Videotapes of the crash tests were shown to Caltrans engineers. Vehicle and barrier performance appeared to be quite good. The reported lateral displacements were between one inch (0.025 m) and 16 inches (0.4 m). The

FIGURE 3

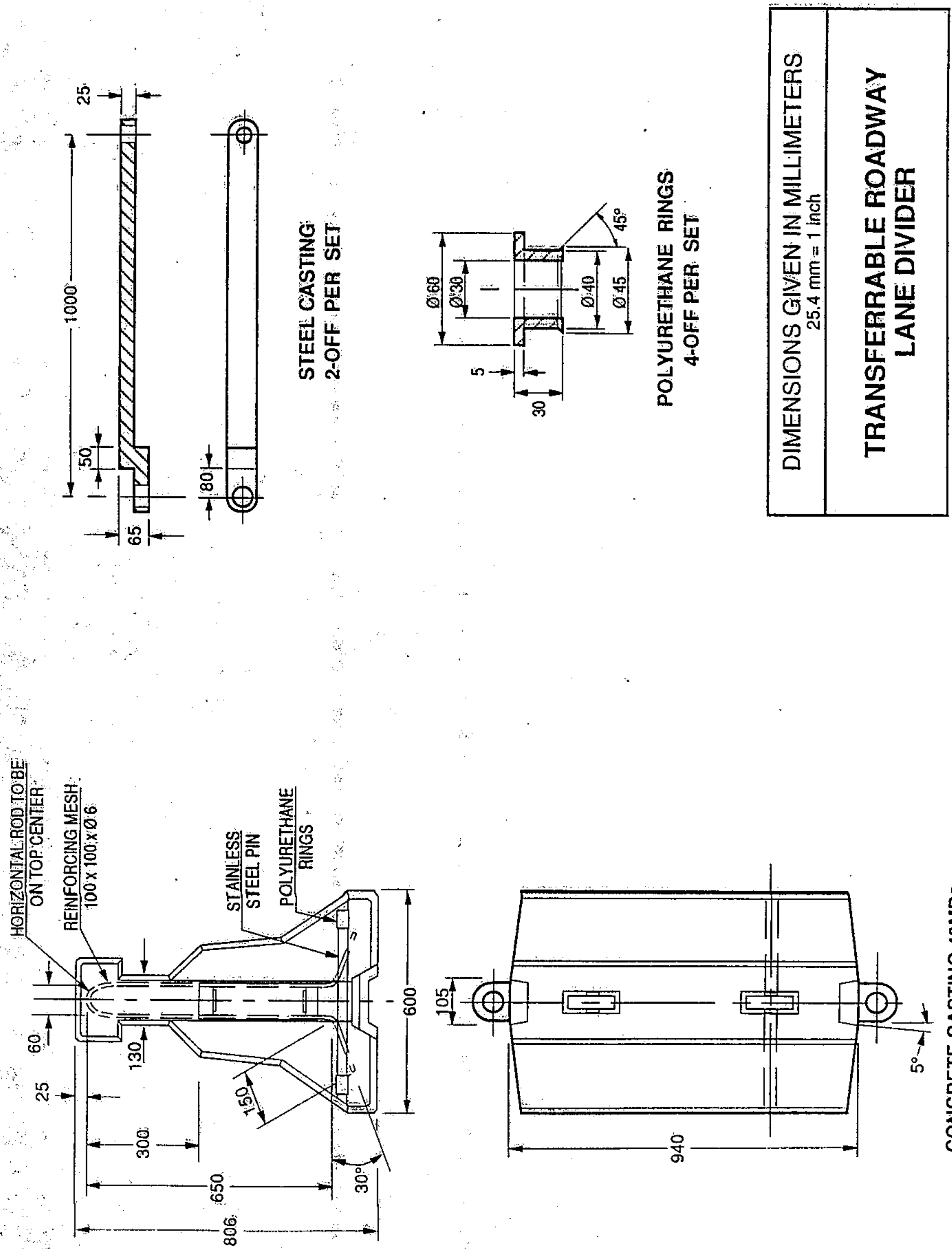


FIGURE 3. LOOSE MCB WITH PIN AND LINK HINGED JOINT - AUSTRALIAN DESIGN

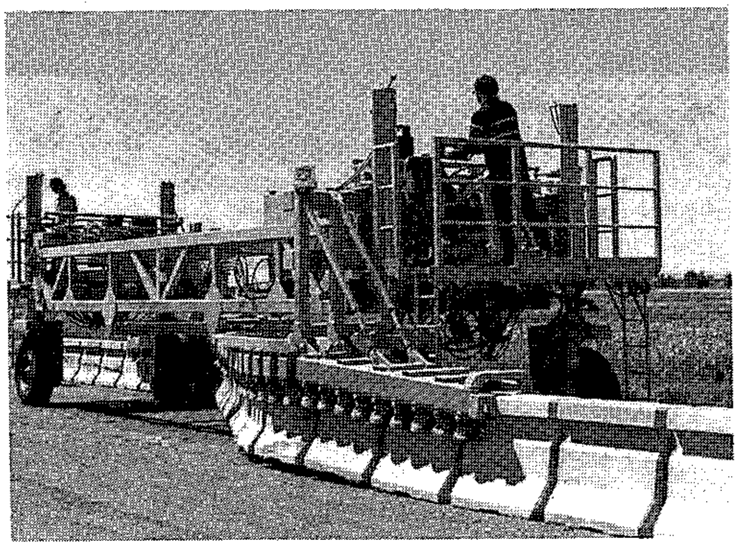


FIGURE 4

SELF-PROPELLED TRANSFER VEHICLE;

Conveyor wheels lift concrete segments that are guided by S-shaped conveyor and then lowered to the pavement.

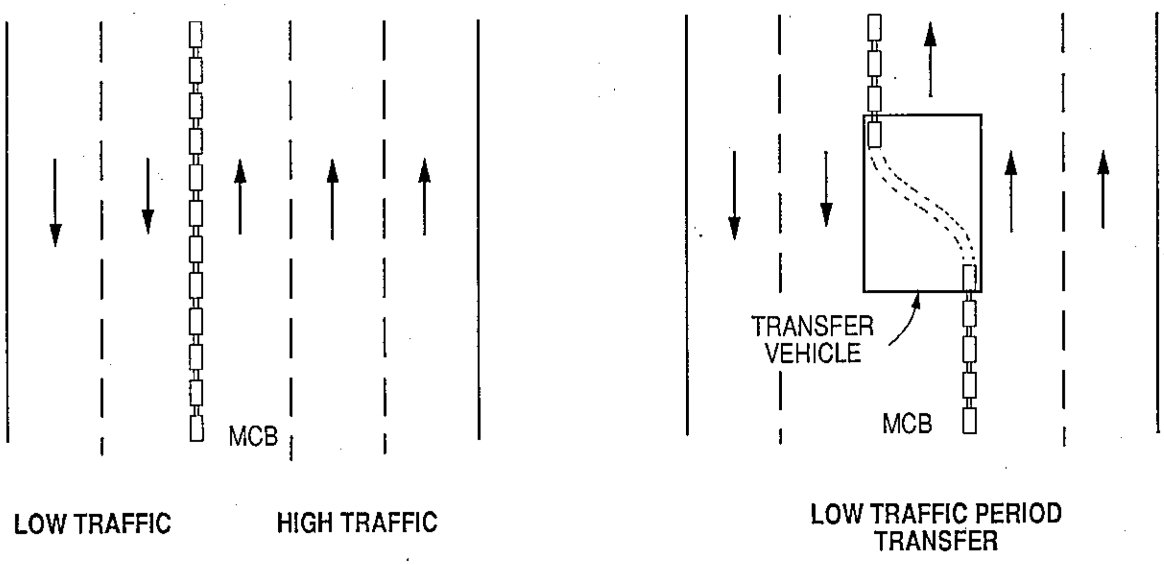


FIGURE 5

PROTECTION OF THE TRANSFER VEHICLE FROM TRAFFIC BY THE BARRIER AND THE SHADOW OF THE TRAFFIC

highest lateral displacement was observed in a channel lock joint barrier impacted by a 4,400-lb (1996 kg) car at a 15 degree impact angle and 45 mph (20.1 m/s). The vehicle was redirected fairly smoothly parallel to the barrier; vehicle and barrier damage were light.

Results of the Australian tests created strong interest in the MCB at Caltrans. Before approving it for use, however, Caltrans engineers concluded that it should be subjected to the tests recommended in NCHRP Report 230 (3). This federally funded research project was initiated by Caltrans and was a joint effort by Caltrans and Barrier System, Incorporated(BSI). BSI supplied a test barrier in place and conducted demonstrations of the transfer vehicle. Caltrans conducted the crash tests, collected and analyzed data and wrote the research report.

1.4 LITERATURE SEARCH

In a comprehensive movable median barrier feasibility study published in November 1983, the following comments were made concerning five systems in existence (4):

1. At the south approach to the Sydney Harbor Bridge in Australia there is a curb-like median strip, that is 4-feet (1.2 m) wide, 230-feet (70 m) long and composed of steel modules 13-feet (4 m) long with reflective semi-flexible posts on top. The first module of the median strip contains a drive mechanism that moves the entire barrier. This barrier channelizes traffic at the throat of reversible lanes near a toll plaza. Improved models have been developed for freeway locations near Sydney. This curb barrier has been reliable, but is too low to redirect vehicles impacting at high speeds.

2. At Caldecott Tunnel, Orinda, California, pneumatically operated pop-up tubes were installed at the approach to reversible lanes. A regular maintenance program is needed to keep the tubes operational. The tubes serve only as delineation, not as a barrier.

3. At the Coronado Bridge, San Diego, California, a modified, compact pop-up tube system was installed similar to the one at Caldecott Tunnel. Because of the need for frequent mechanical and electrical repairs on the

tubes, they were replaced with delineation stanchions that are manually placed. Neither system served as a vehicle barrier.

4. On Interstate 70 in St. Louis, Missouri, there is a 336-foot (102 m) long retractable guardrail system composed of fourteen 400-lb (181 kg) blocks, each 24-feet (7.3 m) long, 2-feet (0.6 m) high and 3-feet (0.9 m) wide, that are pulled into position by a motor driven cable. The blocks are guided on rails set flush with the pavement. The barrier blocks a reversible roadway entrance when operation is in the opposite direction and is pulled out of the way onto the median when the entrance is open. Repairs were needed often due to weather, debris, and impacts. In 1976, the barrier motive system was removed and a tow truck is now used to move the barrier. This type of barrier could not be used as a continuous median barrier capable of lateral movement to change the barrier position.

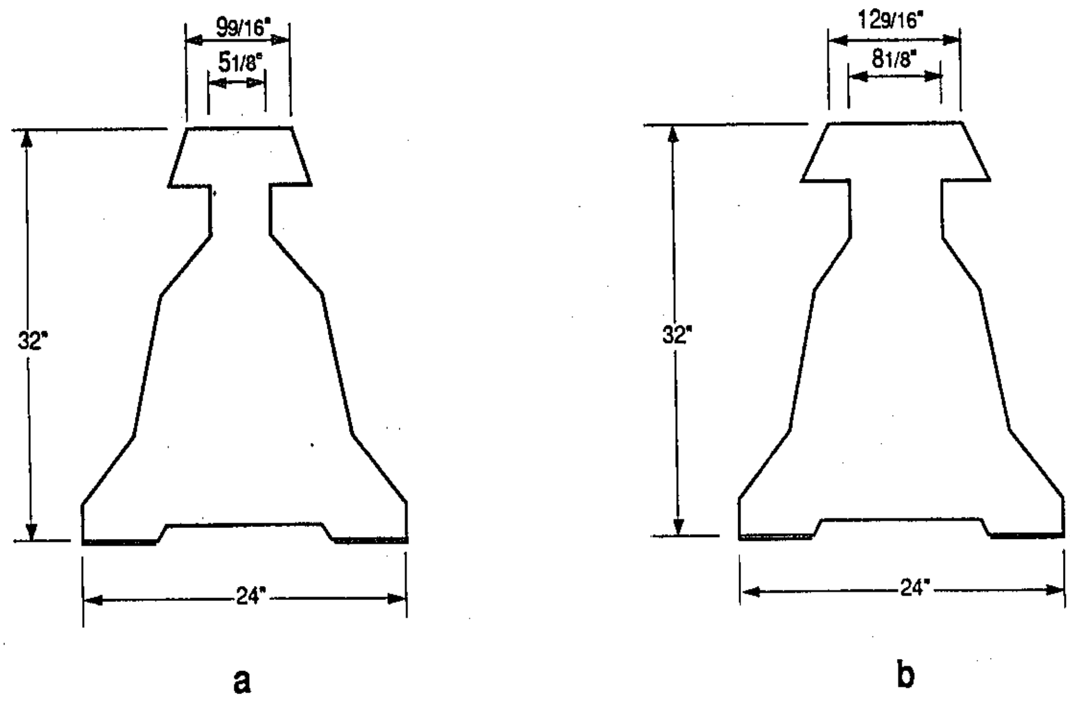
5. On Lake Shore Drive, Chicago, Illinois, hydraulically operated fins were placed on every other lane line of an 8-lane roadway. The fins were placed in a trench and were flush with the pavement when lowered. The fins were steel boxes 20-inches (0.5 m) wide by 16-inches (0.41 m) high by 25 feet (7.6 m) long and were raised 8 inches (0.2 m) above the roadway with hydraulic jacks to act as a barrier. Maintenance was constant and costly. The barrier was shortened and eventually not used after lane reversal operations were curtailed.

In summary, very few movable barriers are in existence, some are delineation devices rather than vehicle barriers, most have been maintenance headaches, and none were designed for use as median barriers of indefinite length that could be changed from one lane line to another. Schemes proposed in past years to Caltrans, briefly mentioned as impractical in the Background Section, were never documented in published research papers or reports.

A series of crash tests and demonstrations of a precast movable concrete barrier were performed. There were a total of six crash tests on three MCB designs and four different operational demonstrations using the barrier transfer equipment.

The cross sections of the barriers used for this test series are shown in Figure 6. For test 441 and 442 a Configuration F shape barrier design (5) was modified to accommodate lifting by the transfer vehicle (Figure 6a). In test 441 the 3.28-foot (1 m) long segments were connected with a pin and link hinge with a longitudinal clearance of one inch (0.025 m) (Figure 7). In test 442 the same segment and hinge design was used with the addition of a 6-foot (1.85 m) long channel in a notch in the base of the barrier. The channel bridged two joints to make the barrier more rigid. Crash tests on this barrier were unsuccessful due to gross barrier failure.

FIGURE 6. CROSS SECTIONS OF BARRIERS



a - Test 441 and 442 Barrier

b - Test 443 through 446 Barrier

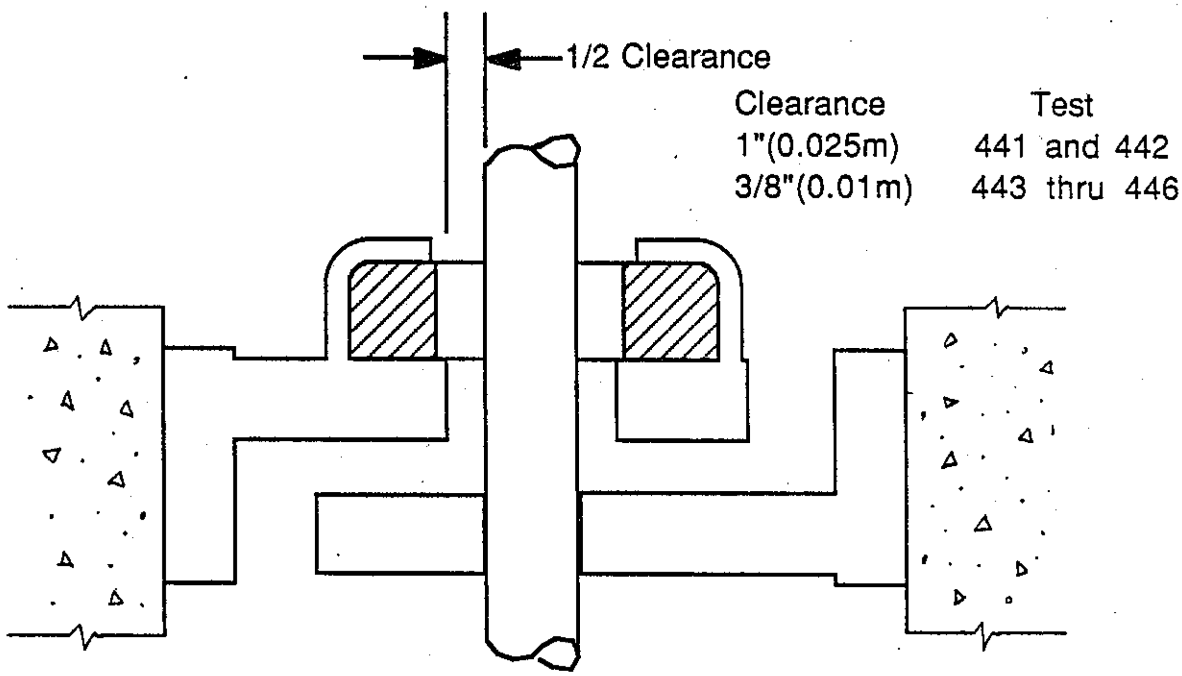
1-inch = 0.0254 m

Tests 443 through 446 used a cross section (Figure 6b) which had a reinforcement cage and a larger minimum stem thickness than tests 441 and 442 although it was still based on the Configuration F shape. The 3.28-foot (1 m) long segments were connected with a pin and link hinge with a longitudinal clearance of 3/8 inches (0.01 m) (Figure 7). There were no devices to limit the flexibility of the barrier. The same barrier segments were used in each of the last four tests.

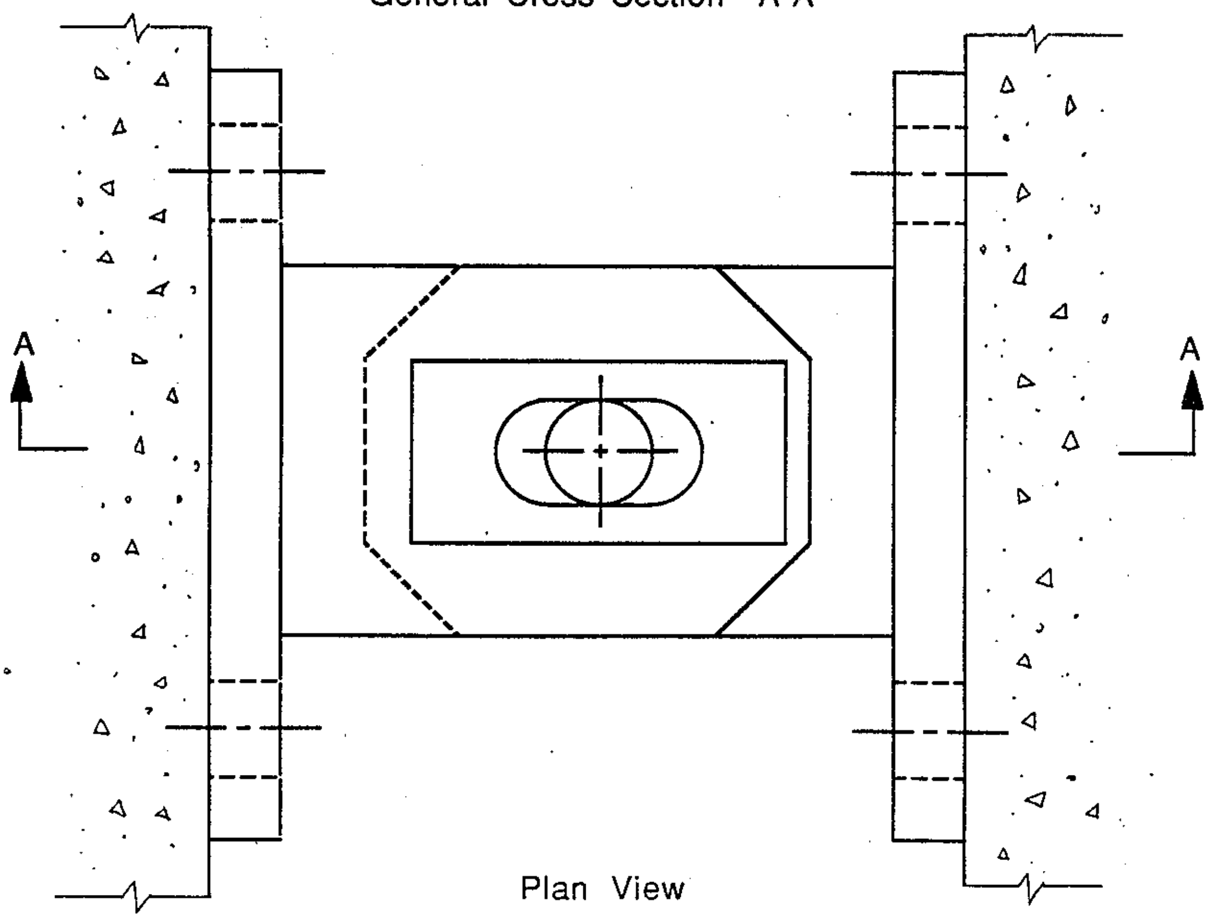
The four demonstrations involved in this project were as follows: transfer vehicle straightening the deflected barrier after the last crash test; transfer vehicle transporting, assembling and transferring barrier on a 1400-ft. (427 m) radius with a 12% cross-slope; transfer vehicle transferring barrier on a 4 to 5% longitudinal grade; manually moving the barrier to adjust minor misalignments. In other work, the manufacturer also demonstrated and videotaped manually opening a nine-foot (2.7 m) wide opening in the barrier for an emergency access.

The MCB used in tests 443, 444, 445 and 446, for the most part, performed its intended functions well. The barrier is easily transferred with a self-powered transfer vehicle and it can be moved easily by a single person with an ordinary pry bar. It smoothly redirects large and small cars impacting at approximately 60 mph (26.8 m/s) with minimum risk to occupants and minimal generation of debris. This barrier can prevent serious head-on collisions when deployed as a median barrier. It can also provide secure protection for workers when deployed as a construction zone barrier. Although there is lateral deflection of the barrier, slight protrusion of the barrier into the protected zone is generally more desirable than uninhibited intrusion of a fast-moving vehicle into the protected zone.

FIGURE 7
HINGE CONNECTIONS OF BARRIER SEGMENTS



General Cross Section A-A



Plan View

3. CONCLUSIONS

Based on the results of the six impact tests on movable concrete barriers and four demonstrations of the transfer vehicle conducted in the course of this research project, the following conclusions can be drawn:

1. Small cars can be smoothly redirected by the movable concrete barrier (MCB) with satisfactory occupant risk factors.

2. The MCB is strong enough to fully contain a 4500 lb (2041 kg) vehicle at 60 mph (26.8 m/s) /25 degrees with no structural failure and little debris generation.

3. The flanged top, which is used to lift the barrier limits the distance a vehicle climbs the face of the barrier and thus limits the roll angle of the vehicle.

4. The MCB deflects laterally under impact. The barrier system, using a pin and hinge connection with a longitudinal clearance of 3/8 inches (0.01 m) (Tests 443-446), exhibited a reduced lateral barrier displacement compared to that expected when the hinge clearance was 1 inch (0.025 m) (Tests 441-442).

5. In all tests, the exit speeds and angles of the cars did not strictly meet NCHRP Report 230 requirements. However, the vehicle post impact trajectory resulted in a smooth redirection of the car outward and, sometimes, toward the movable concrete barrier.

6. Lateral deflection of the MCB has a strong statistical relation to impact severity ($IS = 1/2\ MV^2 \sin\theta^2$, where M = vehicle mass, V = vehicle speed, θ = impact angle).

7. The transfer vehicle can easily and smoothly move the barrier one full lane width (6 to 16 feet, 1.8 to 4.9 m) at speeds up to 6 mph (2.7 m/s).

8. A barrier that is deflected as much as 2.24 feet (0.68 m) can be straightened by the transfer vehicle or can be pushed back into place by one person with a pry bar.

9. Transporting, assembling, and transferring a MCB on a 1400 ft, (427 m) radius curve with a 12% cross slope, and transferring the barrier on a 5% longitudinal grade can be successfully performed by the transfer vehicle.

4. RECOMMENDATIONS

1. The movable concrete barrier (MCB) is recommended for use as a permanent longitudinal traffic barrier and as a construction zone barrier. When planning a use of this MCB, consideration must be given to the expected lateral displacement under impact.

2. Attention should be given to barrier longitudinal creep where installed on a grade.

3. The MCB should be used first on a trial basis and subjected to an in-service evaluation as outlined in Chapter 3 of NCHRP Report 230 (3). If the first installation is in a construction application, operational experience can be gained by the department before a permanent barrier is installed.

4. When using the transfer vehicle, pavement surface condition should be closely monitored.

5. Using the relationship for deflection versus impact severity developed in this report, potential users should predict maximum barrier deflection expected and determine whether there is sufficient space at the site to accommodate the deflected barrier safely.

5. IMPLEMENTATION

The Division of Traffic Engineering will be responsible for preparation of plans and special provisions for use of the MCB. Also, the Division of Traffic Engineering will prepare memoranda to designers regarding proper use and design limitations of the MCB. Technical support for the above will be provided by the Office of Transportation Laboratory.

6. TECHNICAL DISCUSSION

6.1 TEST CONDITIONS

6.1.1 Test Facilities

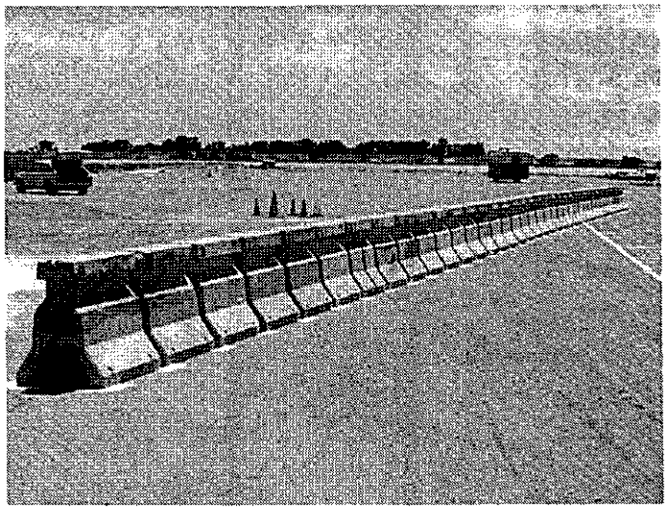
All the crash tests in this series were conducted at the Caltrans Dynamic Test Facility in West Sacramento, California. The tests were performed on a large, flat asphalt concrete surface. The test barrier was placed on the pavement. There were no obstructions nearby except for a 5-foot to 6-foot (1.5 to 1.8 m) high earth berm about 90 feet (27 m) downstream from the test barrier.

6.1.2 Test Barrier Design

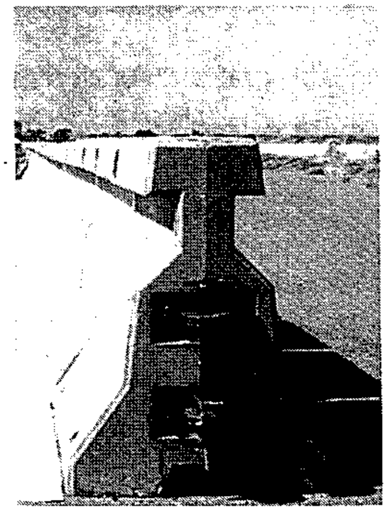
The test barrier was composed of reinforced concrete segments. Concrete minimum compressive strength was 4000 psi. It was manufactured by Barrier Systems, Incorporated (BSI) under the trade name of Quickchange Movable Concrete Barrier. The segments were 3.28 feet (1 m) long, 24 inches (0.6 m) wide at the base, 32 inches (0.8 m) high. They use the shape of Configuration F cross section with some modification. Two types of cross section were used. Figures 6, 8 and 9 show barrier cross sections.

The upper portion of the modules used in tests 441 and 442 was 9-9/16 inches (0.24 m) wide with a 5-1/8 inch (0.13 m) thick neck beneath the cap (Figure 6a and 8b). A longitudinal keyway 8-inches (0.20 m) wide by 3-inches (0.08 m) deep was formed in the bottom of each concrete module. The test barrier was 131.2-feet (40 m) long and consisted of 40 segments (Figure 8a). Twenty-five concrete modules in this barrier had steel fiber reinforcement. The other 15 segments had 6x6-W5xW5 welded wire fabric reinforcement. The location of these two types of reinforced modules was different in tests 441 and 442. A simple hinge connection between segments was used in test 441. Two hinge plate weldments, the upper and the lower, were connected to each end of each module by means of steel "thru" rods. The upper and lower hinge assemblies were identical, but were positioned so that the hinge plates of one module were between the hinge plates of the adjacent. This prevented possible vertical movement between adjacent modules. The hinge-pin holes were 1 3/16 inches (0.03 m) in diameter. The holes in the plate from the other module were

FIGURE 8
TEST BARRIER FOR TESTS 441 AND 442

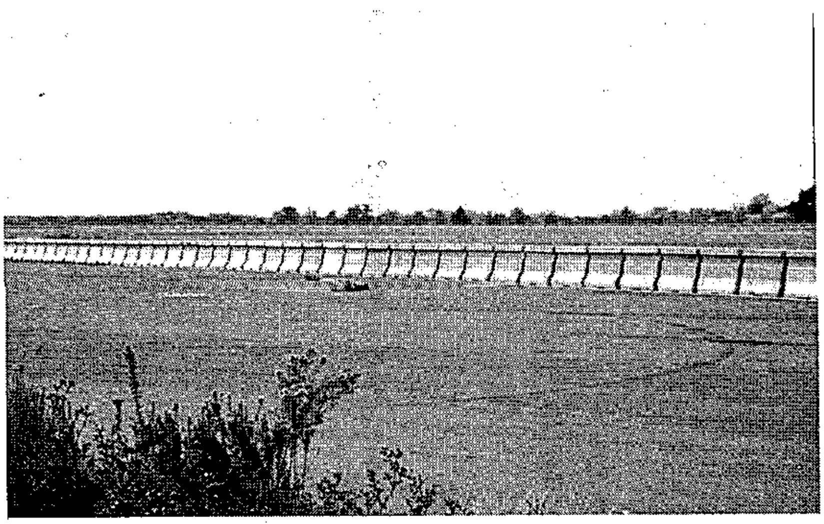


40-Segment Barrier

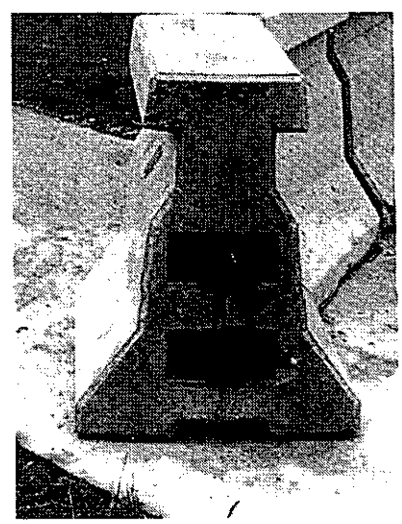


Close-up of Barrier Cross Sections

FIGURE 9
TEST BARRIER FOR TESTS 443 THROUGH 446



100-Segment Barrier



Close-up of Barrier Cross Section

slotted to allow ± 1/2 inch (0.013 m) of longitudinal movement between adjacent modules. The longitudinal clearance was thus 1 inch (0.025 m). A 1-1/8-inch (0.029 m) diameter steel pin completed the connection between two adjacent segments. In test 442, in addition to the above mentioned hinge-pin design, a steel channel 6 feet (1.85 m) long was set in the longitudinal keyway in the underside of the barrier segments. The channel bridged across two joints to make the barrier more rigid than in test 441.

In tests 443 thru 446 the top of the barrier cross section was widened to 12-9/16 inches (0.318 m); the neck was also widened, to 8-1/8 inches (0.206 m) (Figure 6b and 9b). The complete test barrier plans are shown in Appendix D.. A longitudinal notch 8-inches (0.20 m) wide by 1-1/2 inches (0.038 m) deep was in the bottom of each concrete module. The test barrier was 328 feet (100 m) long, 100 segments (Figure 9a). Each module was reinforced with two rebar stiffeners (ASTM A615) and 4x4- W4xW4 welded wire fabric (ASTM A185). The reinforcement pattern is shown in Figure D2 (Appendix D). Hinges were bolted to four 7/8-inch (0.022 m) diameter steel "thru" bars (ASTM A37) 36 inches (0.9 m) long which acted as reinforcement as well. The upper and lower hinge assemblies were identical, but were positioned so that the hinge plates from one adjacent module were between the hinge plates from the other. Each hinge plate assembly contained 7/8-inch (0.022 m) plate welded to 3/4-inch (0.019 m) plate. Plates are made of ASTM A36 steel. The details of the welded steel hinge assemblies are shown in Figures D3 and D4 (Appendix D). The hinge-pin holes were 1-1/4 inches (0.032 m) in diameter. The slot length was 1-1/2 inches (0.038 m). The longitudinal clearance was, thus, only 3/8 inch (0.009 m). A 1-1/8 inch (0.029 m) diameter steel pin (Aisi 4140) completed the connection between two adjacent segments. A 1 inch (0.025 m) thick compressible material (80 Durometer neoprene, 1000 psi) pusher plate was attached to each hinge steel plate to keep the hinge pin centered as much as possible (Figure D5 - Appendix D).

The base of each segment had four 7 in. x 7 in. (0.18 m x 0.18 m) polyvinylchloride (PVC) pads, one on each corner. The pads were made of 70-73 Durometer PVC, rough top with working tension 150 lb (68 kg) and were supplied by Scandura, Inc., North Carolina. The pads had three layers: 70-lb

(32 kg) woven polyester back, PVC bonding and PVC rough surface. The pads were glued on barrier segments with Sikaflex #241 glue.

6.1.3 Test Barrier Construction

Barrier Systems, Inc. supplied and installed the barriers for all tests. A forklift was used that handled one segment at a time. The segments were free standing on the asphalt concrete pavement.

In tests 441 and 442 the barrier was 40 segments long. The placement and deployment of the barrier for test 441 took about two days.

The same barrier segments were used in test 442; only the segment locations were changed. The repositioning of test segments and the addition of steel channel in the longitudinal keyway in the underside of the barrier segments took about one day.

In tests 443 through 446 the barrier was 100 segments long. The first installation of the new barrier took about half a day. For each of the following tests, the segments from the former impact area were moved to the end of the barrier; thereby a clean barrier face was always exposed in the new impact area. Shifting the segments and straightening the barrier usually took about half a day. When a change in impact angle was required (tests 444 and 446), the barrier chain was completely disassembled and reformed at the new angle of impact measured against the fixed guidance cable. Additional time - a quarter to a half day - was spent for this repositioning. The barrier preparation for test 444 was done in about one day due to supplementary maneuvers such as turning segments around.

6.1.4 Test Vehicles

The test vehicles complied with NCHRP Report 230(3). For all tests, the vehicles were in good condition and free of major body damage and missing structural parts. All equipment on the vehicles was standard. The engines were front mounted. No ballast was used. Vehicle types used in the tests and their weights are shown in Table 1.

TABLE 1

Test No.	Vehicle	Weight-lb (kg)*
441	1980 Ford Station Wagon	4210 (1910)
442	1982 Ford Station Wagon	4020 (1823)
443	1982 Olds Station Wagon	4370 (1982)
444	1981 Honda Civic	2000 (907)
445	1982 Olds Station Wagon	4300 (1950)
446	1984 Nissan Sentra	1890** (857)

* Weight without dummy
** Nonessential parts were removed from the car to adjust the car weight closer to 1800 lb (816 kg).

Car front-end profile measurements were taken before and after tests.

The vehicles were self-powered; a speed control device maintained the desired impact speed once it was reached. Remote braking was possible after impact. Guidance of the vehicle was achieved with an anchored cable which passed through a guide bracket on the right front wheel of the vehicles. No constraints were put on the steering wheel. A short distance before the point of impact, the vehicle was released from the guidance cable and the ignition was turned off. A detailed description of the test vehicle equipment and guidance system is contained in Appendix A.

All impacts were on the left (driver) side of the vehicles.

6.1.5 Data Acquisition Systems

The impact phase of each crash test was recorded with several high speed movie cameras, one normal speed movie camera, one black and white sequence camera and one color slide sequence camera. The test vehicles and test barriers were photographed before and after impact with a normal speed movie camera, a black and white still camera and a color slide camera. A film report of this project was assembled using edited portions of the movie coverage.

Three accelerometers were attached to the floor of the vehicle near the center of gravity to measure motion in the longitudinal, lateral and vertical directions. Rate gyro transducers were also placed at this location to measure the pitch, roll and yaw of the vehicle. The accelerometer data were used in calculating the occupant impact velocity.

An anthropomorphic dummy with three accelerometers mounted in its head cavity was placed in the driver's seat of the test vehicle to obtain motion and acceleration data. The dummy, Willie Makit, a Part 572 dummy built to conform to Federal Motor Vehicle Safety Standards by the Sierra Engineering Company, simulates a 50th percentile American male weighing 165 lb (74.8 kg). The dummy was placed in the driver's seat and not restrained.

A Norland Model 3001 waveform analyzer was used for data reduction. A Pacific Instruments Model 5600 digital data acquisition system (PACDAS) was used in tests 443 and 445. The Model 5600 is a 32 channel portable data recorder for field applications. It conditions, amplifies, digitizes and records transducer signals at programmable sample rates to 100 kHz per channel. A personal computer was used to program the recorder. Digitized data were recorded in static RAM in the PACDAS; then transferred to, and analyzed by personal computer.

In the two tests in which the PACDAS was used, it was installed in the vehicle and set up to record three accelerometers and event marker signals. The data were used as backup and are presented in Appendix C.

A sliding weight device was used on tests 441 and 442. It was attached to the roof of the vehicle. Upon impact, the weight, fitted with ball bearings, slid two feet (0.61 m) forward on a smooth rod. This was used as a rough check on the "rattlespace" time determined from accelerometer data which was used to calculate the occupant impact velocity. The rattlespace time is the time required for an object to move two feet forward with respect to the passenger compartment after impact.

Appendices B and C contain a detailed description of the photographic and electronic equipment, the camera layout, data collection and reduction techniques, and accelerometer records.

The surveying equipment used for MCB deflection measurements comprised a Wild electronic theodolite T-2000 total station, a Wild DI5 electronic distance measuring device and a Wild electronic data collector GRE3.

The data were electronically recorded on the GRE3 data collector before and after the crash test. Coordinates of each hinge point of the barrier before and after impact were obtained (Tables F9 to F12). Movements of each hinge were determined and they were plotted as a function of hinge number.

6.2. TEST RESULTS

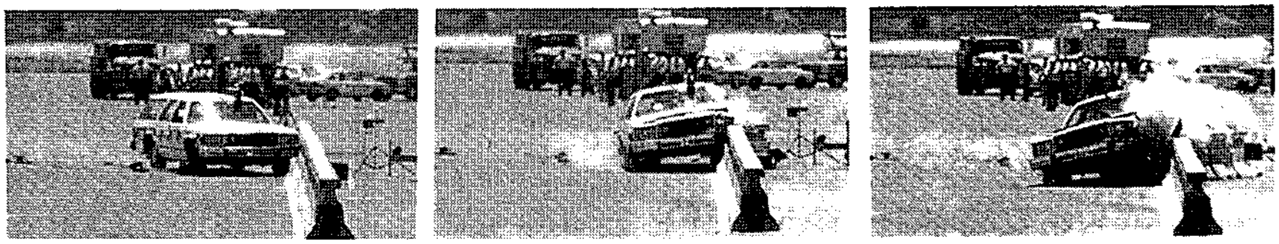
Detailed test results from film and accelerometer data are contained in Appendices B and C.

A film report showing each test is available for viewing.

6.2.1. Test 441-4210 lb (1910 kg) / 59.3 mph (26.5 m/s) / 15-3/4°

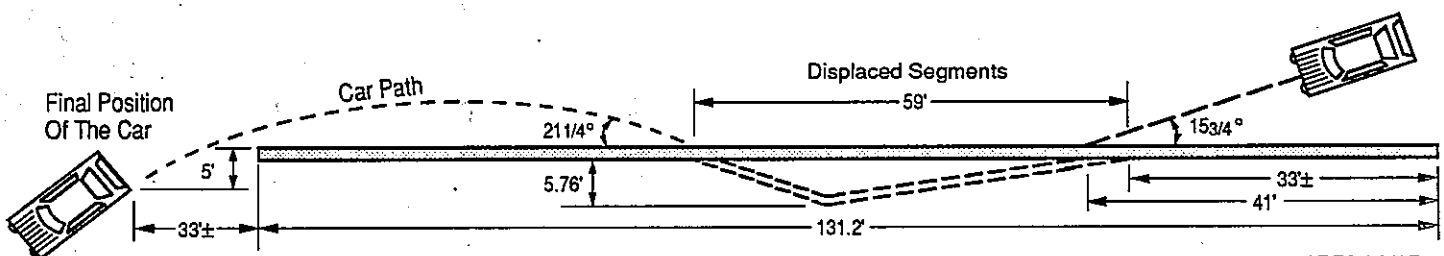
The planned test conditions were: 4210 lb (1910 kg)/60 mph (26.8 m/s)/15 degrees. The Data Summary Sheet and photos taken before and after impact are shown in Figures 10 through 15.

FIGURE 10 Data Summary Sheet Test 441



Impact + 0.005 s | I + 0.155 s | I + 0.39 s

I + 0.688 s | I + 0.993 s | I + 1.37 s



1'=0.3048 m

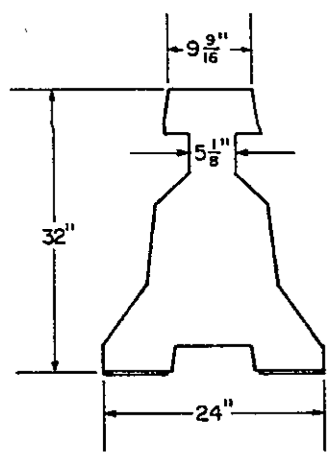
Test Barrier:
- Type: Movable Concrete Barrier (Simple Hinge Connections)
- Length: 131.2 ft (40 m) - 40 segments

Test Date: June 21, 1985

TestVehicle:
- Model: 1980 Ford Station Wagon
- Inertial Mass: 4210 lb (1910 kg)
- Impact Velocity: 59.3 mph (26.5 m/s)
- Impact; Exit Angle: 15 3/4 deg; 21 1/4 deg

Test Dummy:
- Type: Part 572, 50th Percentile Male
- Weight / Restraint: 165 lb (75 kg)/ none
- Position: Driver's seat

Test Data:
- Occupant Impact Velocity (long): 15.5 fps (4.7 m/s)
- Max 50 ms Avg Accel: long –3.6g, lat –4.1g, vert 2.9g
- HIC / TAD / VDI: 36 / LFQ4 / 12LYEEI
- Max Roll;Pitch;Yaw : 14 1/2 deg; 11 1/2 deg; NA
- Barrier Displacement: 5.76 ft (1.76 m) at segment 20
- Max Dynamic Deflection (film): 5.76 ft (1.76 m)
- Barrier Damage: Cracks and failure in the neck section of 4 segments (15 through 18)



1"=0.0254 m

6.2.1.1. Impact Description - 441

The left front bumper of the test vehicle impacted the 40 segment barrier at the midpoint of segment 14, as planned (Figure 11). The impact speed was 59.3 mph (26 5 m/s) at an angle of 15-3/4 degrees. The left front corner of the car contacted the barrier for a distance of about 16.5 feet (5 m). After its initial contact at the downstream corner of segment 13, the left front tire rose to about one foot (0.3 m) above the ground on segment 16 and remained at that elevation for about 10 feet (3 m). The left rear tire initially contacted the barrier at segment 18 and rose about 18 inches (0.46 m) above the ground at segment 20. The length of vehicle contact with the barrier was about 33 feet (10 m) between segments number 14 and 23. The car was smoothly redirected and lost contact with the barrier at an exit angle of 21-1/4 degrees. The vehicle remained upright during and after impact.

During barrier impact, the car experienced a maximum positive roll of 14-1/2 degrees and a positive pitch of 11-1/2 degrees (see sign convention figure in Appendix C). The remote brakes were applied after the car passed beyond the end of the test barrier. The postimpact trajectory of the car was initially away from the barrier. The barrier would have been impacted a second time had it been longer.

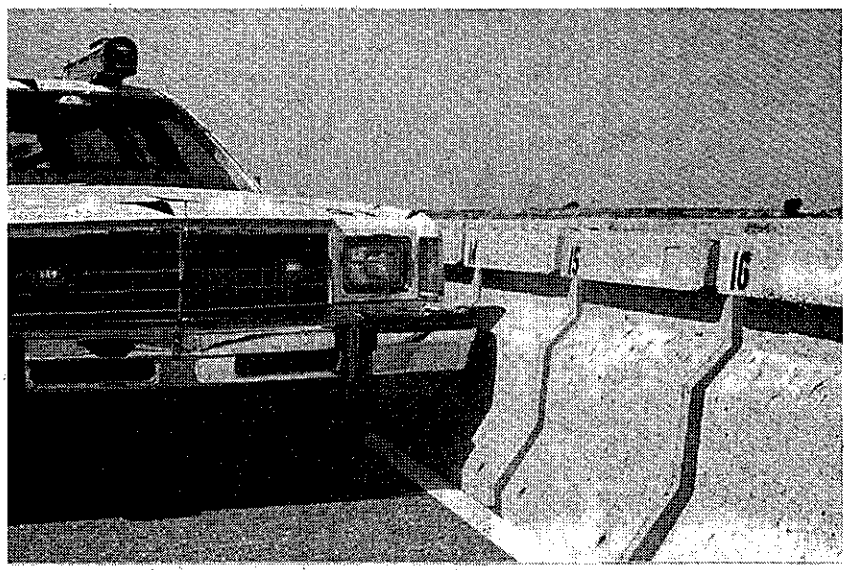
The car came to rest about 33 feet (10 m) from the downstream end of the barrier and 5 feet (1.5 m) from its face (Figure 12).

The maximum 50 millisecond average accelerations were -4.1 g's in the lateral direction and -3.6 g's in the longitudinal direction. The longitudinal occupant impact velocity was 15.5 fps (4.72 m/s). The ridedown accelerations were less than 15 g in both lateral and longitudinal directions.

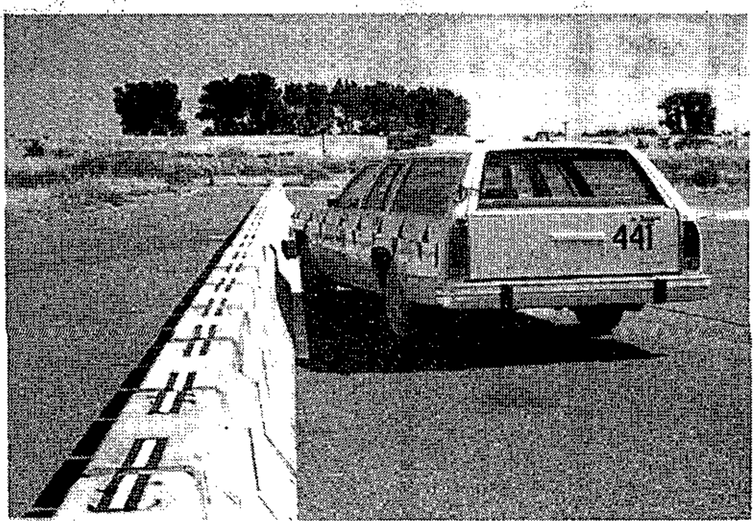
6.2.1.2. Vehicle Damage - 441

The first part on the vehicle to contact the barrier was the left side of the front bumper. Thus, immediately after impact, the left side of the bumper and the entire left fender were crushed. The left doors were jammed and partially

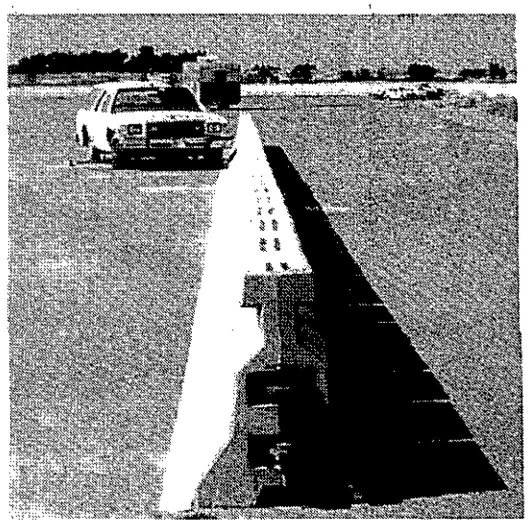
FIGURE 11
TEST 441 TEST VEHICLE AND BARRIER



1980 Ford Station Wagon, 4210 lb (1910 kg)

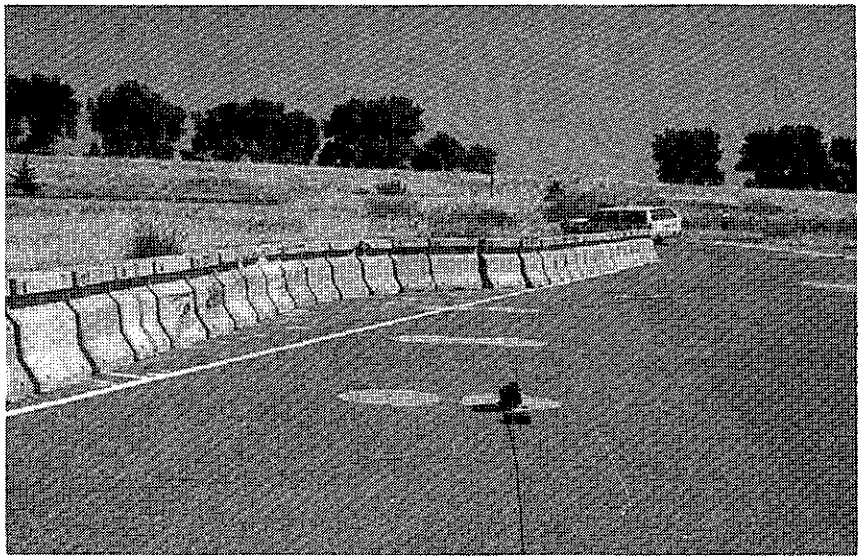


Planned Point of Impact . Midpoint of Segment14



Impact Speed and Angle - 60 mph/(26.8 m/s)/ 15 degrees.

FIGURE 12
TEST 446 FINAL LOCATION OF VEHICLE AFTER IMPACT



crushed on the lower half due to contact with the top of the barrier. The left front wheel was deformed and the tire torn from the rim (Figure 13).

There was no intrusion of vehicle or barrier parts into the passenger compartment during impact.

6.2.1.3. Barrier Damage - 441

The barrier segments in the impact area were 6x6-W5xW5 welded wire fabric reinforced. Damage to the barrier was moderate (Figure 14). Most of the segment edges that were contacted by the car were spalled, producing a large cloud of concrete dust. A substantial number of large fragments up to 3"x5"x15" (0.08 m x 0.13 m x 0.38 m) were generated. A large concrete piece from segment 18 was thrown 176 feet (53.7 m) along the line of

FIGURE 13
TEST 441 VEHICLE DAMAGE

Overall view of Damaged Vehicle.
Crushed left side of the bumper and fender.

Deformed left front wheel and torn tire.

the barrier. The unreinforced overhang of the cap allowed the top part of segment number 18 to be broken. The reinforced necks of segments number 15, 16, 17, and 18 cracked. The cracks developed in the stem were 6-3/4 inches (0.17 m) to 9-1/2 inches (0.24 m) from the top. The face of the barrier received red, yellow and black tire marks and surface scrapings from car sheet metal.

The barrier was displaced laterally along a distance of about 59 feet (18 m) (segments number 9 through 26). The maximum lateral permanent displacement was 5.76 feet (1.76 m) at segment 20 (Figures 15 and 16). Longitudinal displacement was observed at both ends of the barrier but not measured.

6.2.1.4. Dummy's Response - 441

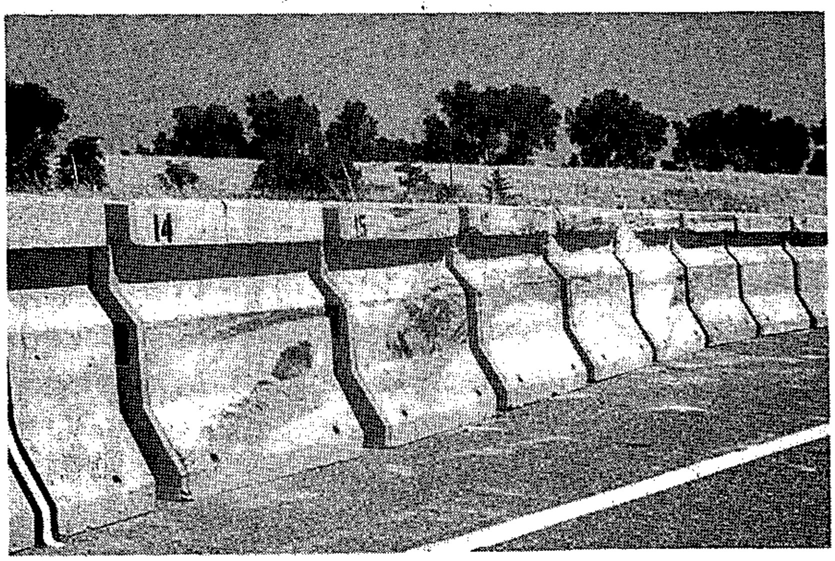
During the impact the unrestrained dummy was thrown ahead and continued to move toward the left corner of the car. In about the middle of the redirective event, the dummy's head and shoulders went out the open left front window. Its chin hit the outside of the door. When the car lost contact with the barrier, the dummy began to move back inside the car, and hit the back of its head on the upper window frame. When the dummy came to rest, its head was still half out of the window, face downward.

There was no physical damage to the dummy.

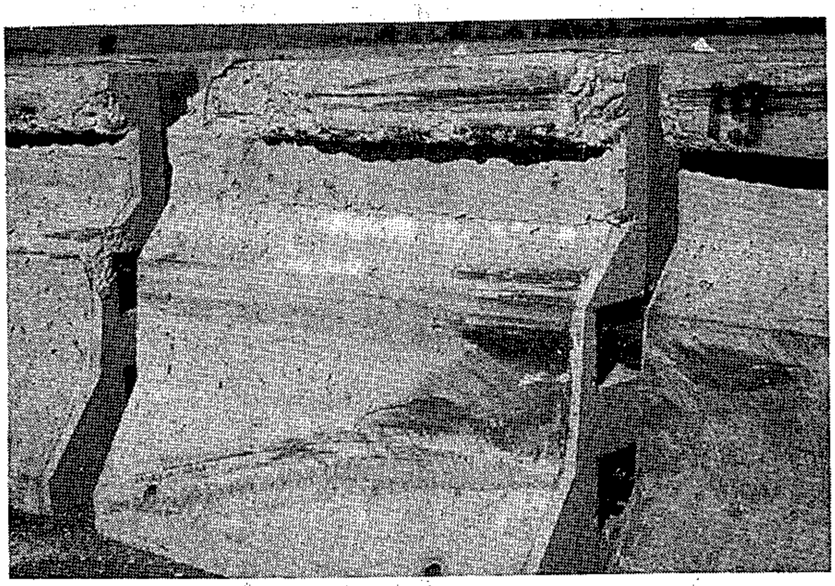
6.2.2. Test 442-4020 lb (1823 kg)/61.9 mph (27.7 m/s)/25-1/2°

The planned test conditions were: 4020 lb (1823 kg)/60 mph (26.8 m/s)/25 degrees. The Data Summary Sheet and photos taken before and after impact are shown in Figures 17 through 24.

FIGURE 14. TEST 441 BARRIER DAMAGE



Overall Barrier Damage. Tire Scuff Marks.



Spalled Concrete Segment 18 and 19. Cracked Neck Segments

Barrier Concrete Chunk

FIGURE 15
TEST 441 BARRIER LATERAL DISPLACEMENT

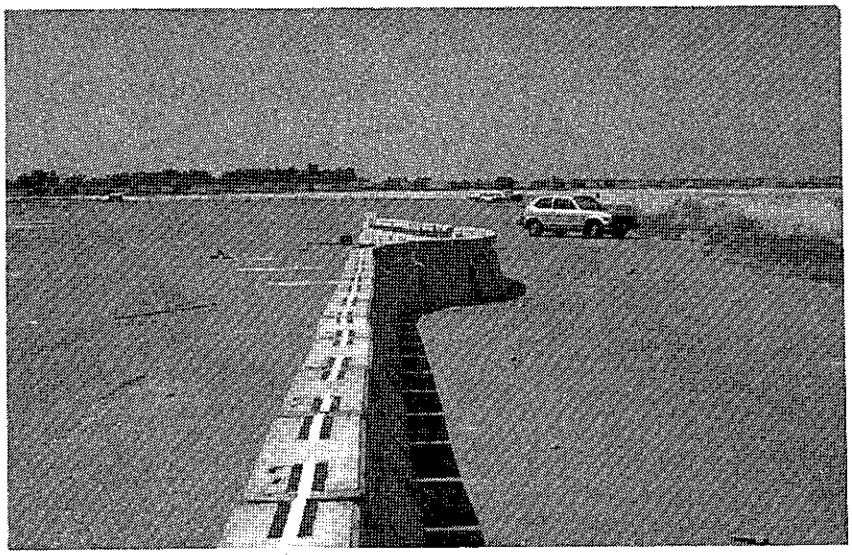
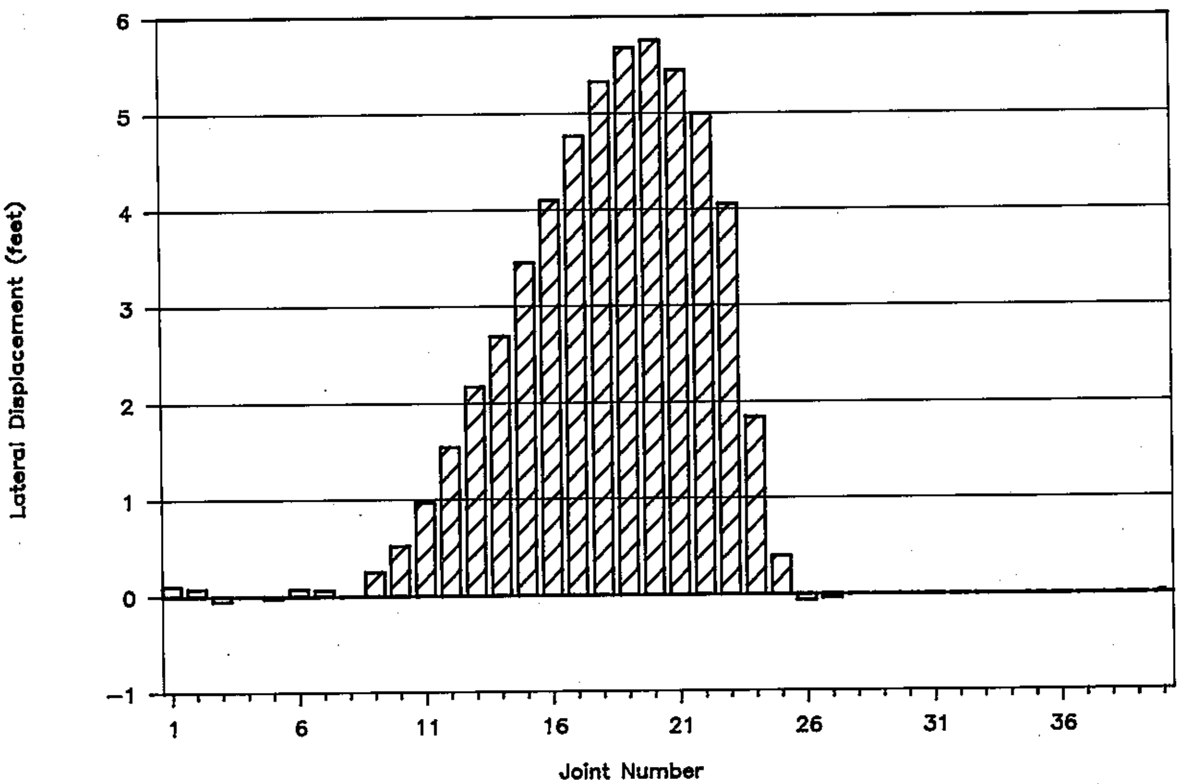


FIGURE 16. TEST 441
BARRIER JOINT LATERAL DISPLACEMENT DIAGRAM



6.2.2.1. Impact Description - 442

The left front bumper of the test vehicle impacted the 40-segment barrier at mid-point of segment 12 as planned (Figure 18). The impact speed was 61.9 mph (27.7 m/s) at an angle of 25-1/2 degrees. The left front corner of the car contacted the barrier for a distance of about 23 feet (7 m). It climbed near the top of the barrier and sheared off the necks and caps of 6 segments (number 14 through 19). The left front tire rose to about 2 feet (0.6 m) above the ground on segment 13 and remained at that elevation for about 6.6 feet (2 m).

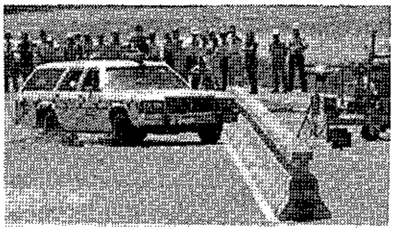
The left rear tire initially contacted the barrier at segment 16 and rose about 2.25 feet (0.7 m) above the ground at segment 17. The length of vehicle contact with the barrier was over 26 feet (8 m) between segments 12 and 20.

The car was smoothly redirected and lost contact with the barrier at an unknown angle. The vehicle remained upright during and after impact. During barrier impact, the car experienced a maximum positive roll of 35-1/4 degrees and negative pitch of 10 degrees. The maximum rise of the car was 63.8 inches (1.6 m) 1.05 seconds after the impact, measured at the left rear corner of the car roof.

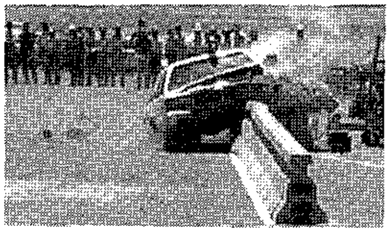
The postimpact trajectory of the car was back toward the line of the barrier. A second impact with the barrier occurred at segment 40. The car came to rest about 1.8 feet (0.55 m) from the downstream end of the barrier (Figure 19).

The maximum 50 millisecond average accelerations were -8.1 g's in the lateral direction and -7.7 g's in the longitudinal direction. The longitudinal occupant impact velocity was 24.7 fps (7.53 m/s). The ridedown accelerations were less than 15 g in both the longitudinal and lateral directions.

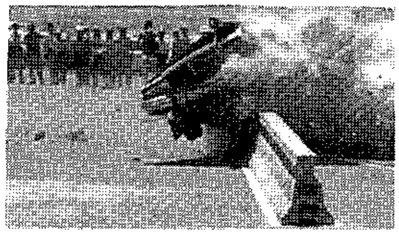
FIGURE 17 Data Summary Sheet Test 442



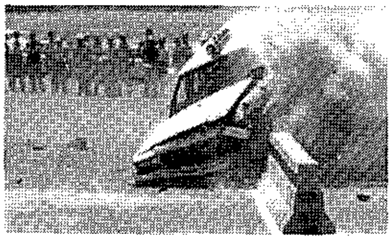
Impact + 0.005 s



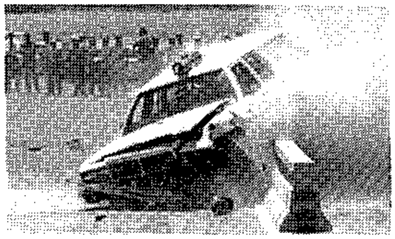
I + 0.226 s



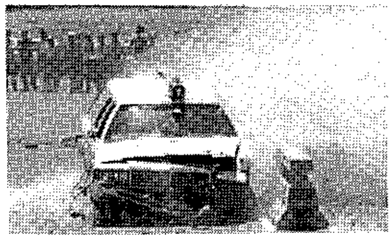
I + 0.528 s



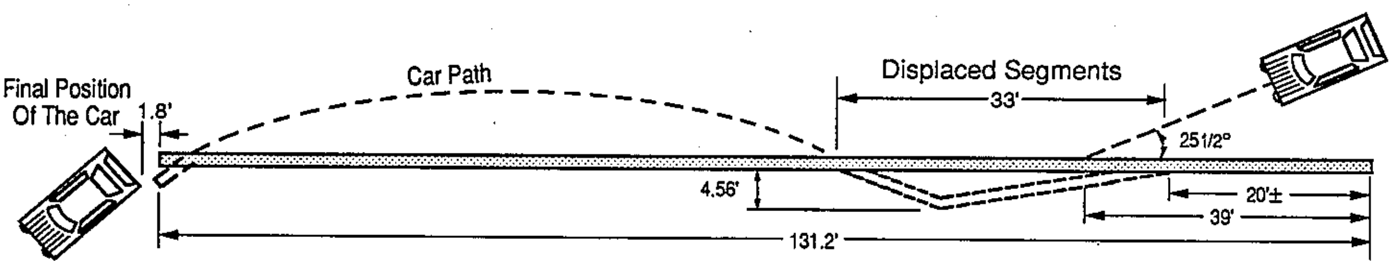
I + 1.006 s



I + 1.663 s



I+ 2.216 s



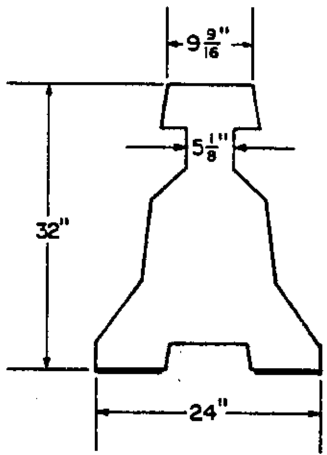
Test Barrier:
- Type: Movable Concrete Barrier (Lock Channel Hinge)
- Length: 131.2 ft (40 m) - 40 segments

Test Date: July 2, 1985

TestVehicle:
- Model: 1982 Ford Station Wagon
- Inertial Mass: 4020 lb (1823 kg)
- Impact Velocity: 61.9 mph (27.7 m/s)
- Impact; Exit Angle: 25 1/2deg; NA

Test Dummy:
- Type: Part 572, 50th Percentile Male
- Weight / Restraint: 165 lb (75 kg)/ none
- Position: Driver's seat

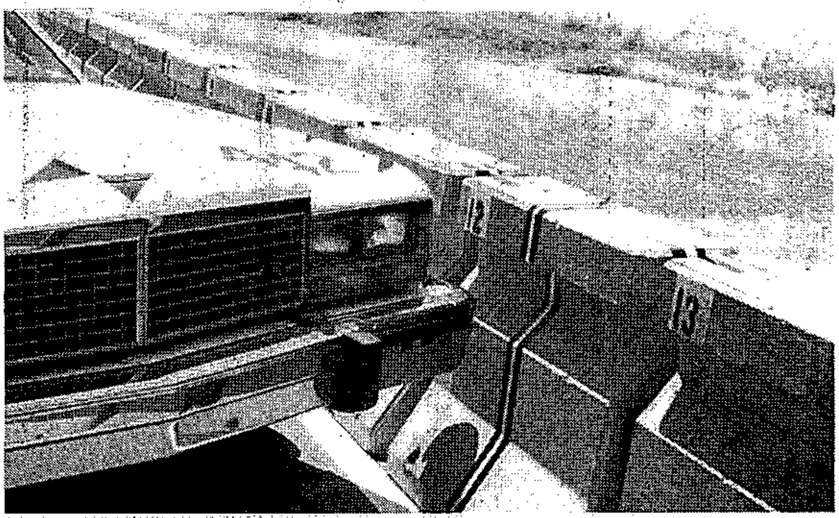
Test Data:
- Occupant Impact Velocity (long): 24.7 fps. (7.5 m/s)
- Max 50 ms Avg Accel: long –7.7 g, lat –8.1 g, vert 4.5 g
- HIC / TAD / VDI: 123 / LFQ5 / 11LFEW3
- Max Roll;Pitch;Yaw : 35 1/4 deg;–10 deg; NA
- Barrier Displacement: 4.56 ft (1.39 m) at segment 15
- Max Dynamic Deflection (film): 4.25 ft (1.29 m)
- Barrier Damage: 9 segments were broken (segments 12 through 20)



1"=0.0254 m

FIGURE 18. TEST 442 TEST VEHICLE AND BARRIER

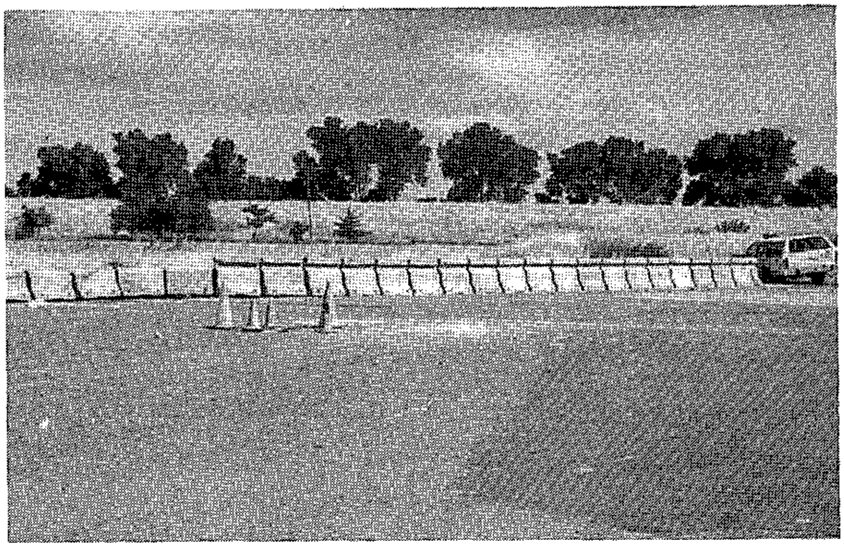
1982 Ford Station Wagon, 4020 lb (1823 kg) at Planned Point of Impact



Planned Point of Impact - Midpoint of Segment 12.

Planned Speed and Angle - 60 mph (26.8 m/s)/25 degrees

FIGURE 19
TEST 442. FINAL POSITION OF CAR



Car at 1.8 feet (0.55 m) from Downstream End of the Barrier.

Final Position of Car.

6.2.2.2. Vehicle Damage - 442

The first part of the vehicle to contact the barrier was the left side of the front bumper. Thus, immediately after impact, not only the left side of the bumper, but the entire front fender including the left headlight were seriously damaged (Figure 20). The left front door was severely crushed. The hood was jammed and remained ajar. The windshield was cracked by the dummy's head during the impact. The left rear fender and door were both crinkled due to the contact with the top of the barrier. The left front wheel was deformed and crushed. The tire was flattened, thus, restricting the movement. The radiator was pushed back to the block, but the engine was unmoved.

There was no intrusion of vehicle or barrier parts into the passenger compartment during impact.

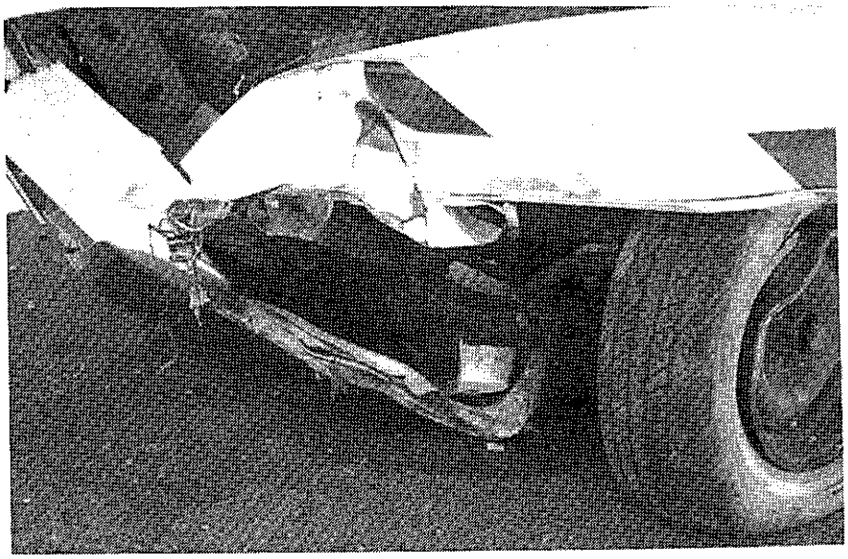
6.2.2.3 Barrier Damage - 442

The barrier segments in the impact area were steel fiber reinforced. Damage to the barrier was substantial (Figure 21). Six segment tops (segments 14 through 19) were completely broken off at the neck section. Three segments (number 12, 13 and 20) had deep cracks in the stem. Most of the barrier segments that were contacted by the car were spalled, producing a large cloud of concrete dust. A number of barrier fragments were also generated. The face of the barrier received red, yellow and black tire marks and surface scraping from car sheet metal.

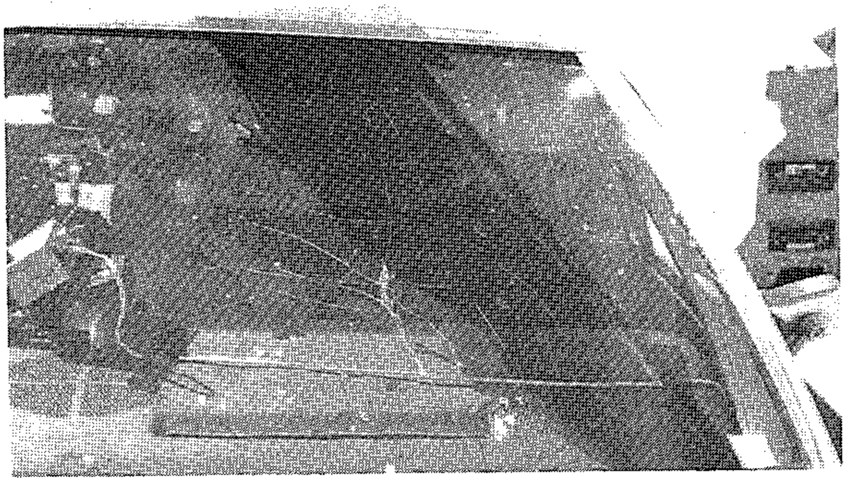
The barrier was displaced laterally along a distance of about 33 feet (10 m) (segments 9 through 18) (Figure 22 and 23). The maximum lateral permanent displacement was 4.56 feet (1.39 m) at segment 15. A second car impact displaced the last three downstream barrier segments. The maximum longitudinal displacement of the barrier was 1.5 feet (0.46 m) at segment 15.

FIGURE 20. TEST 442 VEHICLE DAMAGE

Crushed Left Front Bumper and Fender.

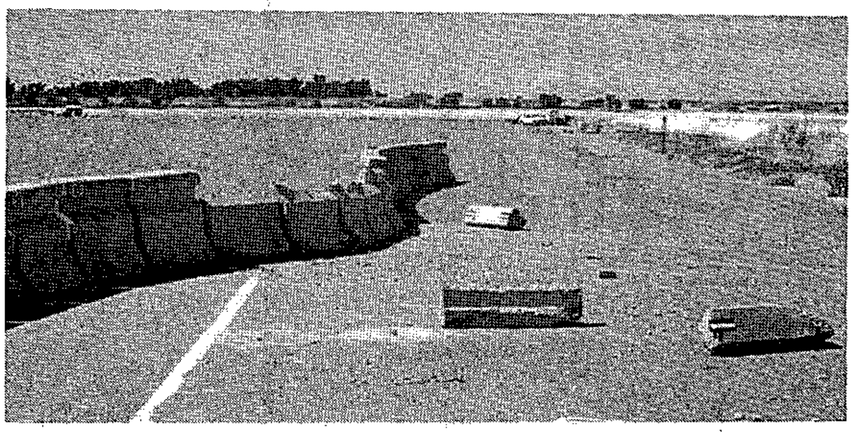


Damaged Left Headlight and Deformed Left Front Wheel.

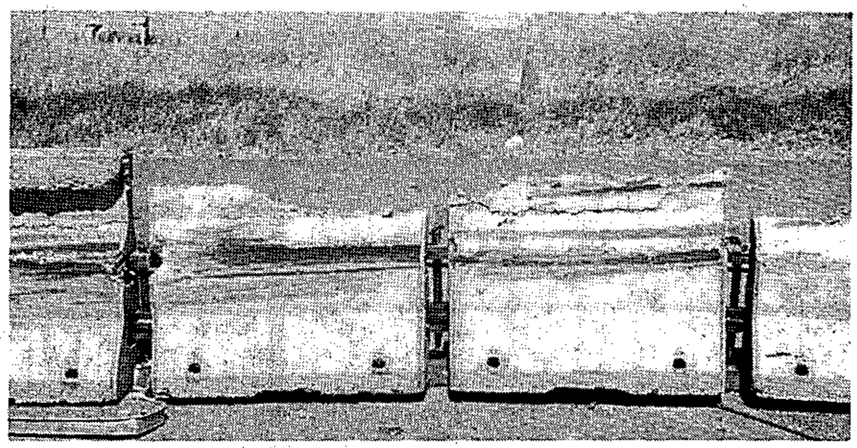


Cracked Windshield

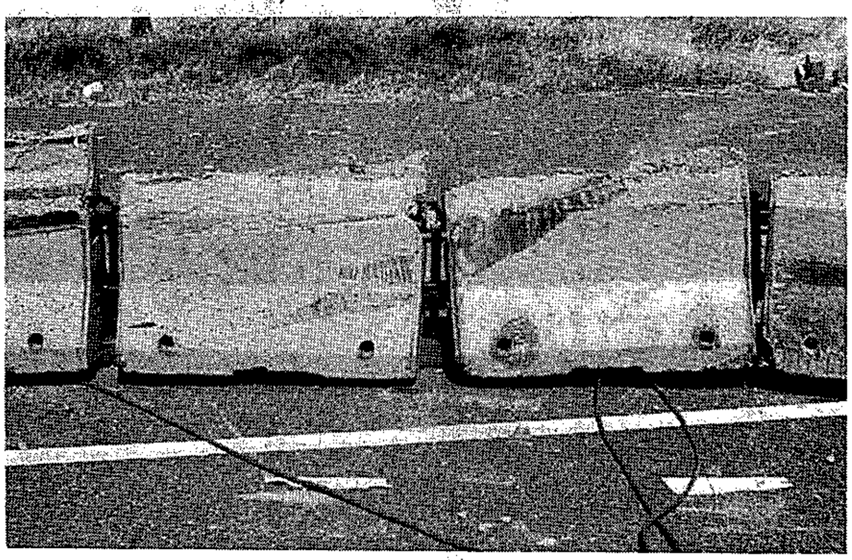
FIGURE 21. TEST 442 BARRIER DAMAGE



Overall Barrier Damage and Segments Thrown Away from the Barrier.

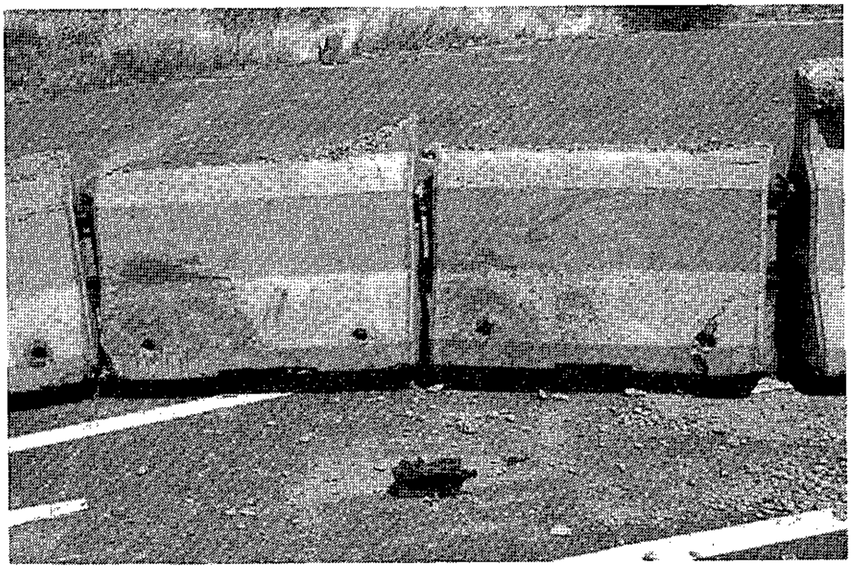


Neck Barrier Damage - Segments 14 and 15.

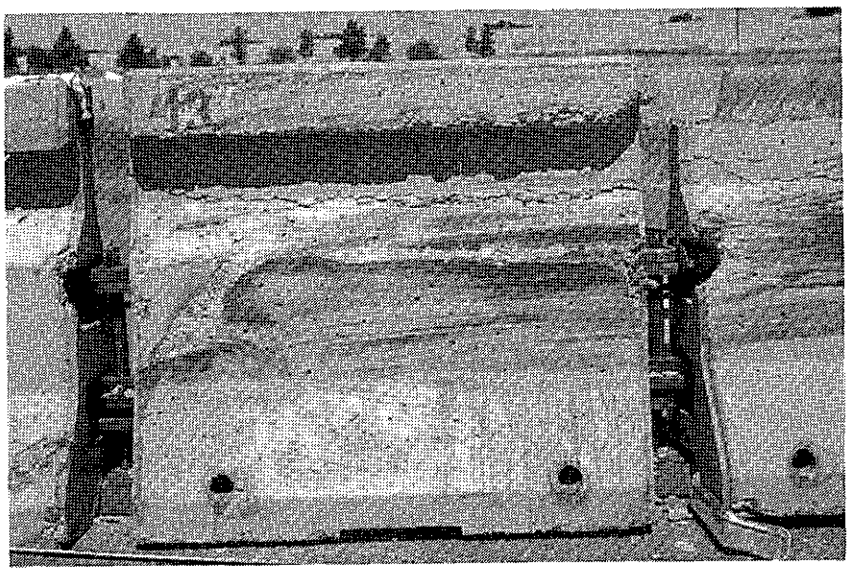


Neck Barrier Damage - Segments 16 and 17.

FIGURE 21. (Continued) TEST 442 BARRIER DAMAGE

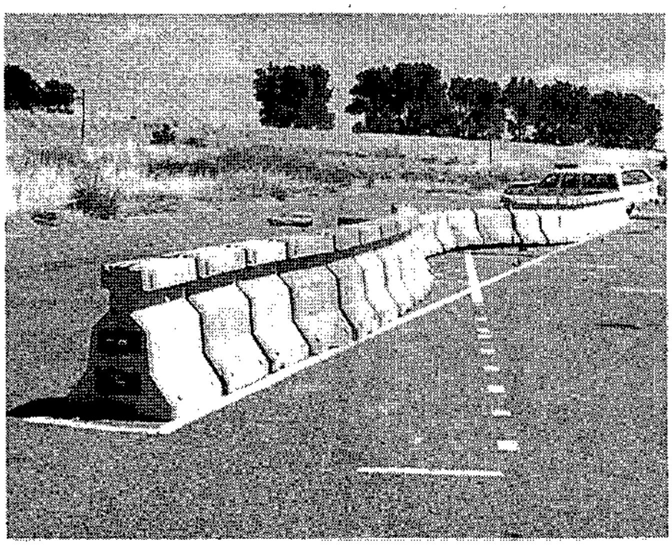


Neck Barrier Damage. Segments 18 and 19.

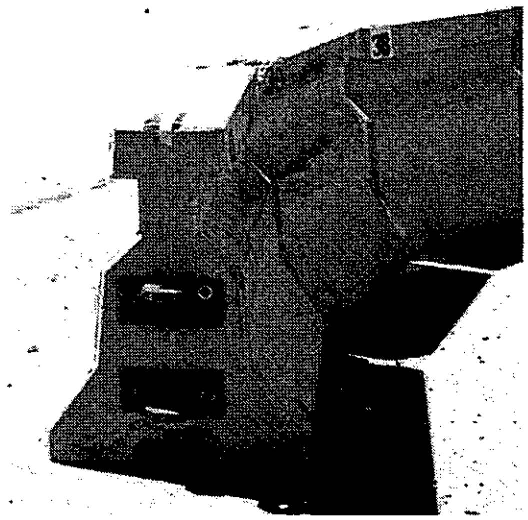


Deep Cracks in the Stem of Segment 13. Tire Marks and Surface Scrapings on Barrier Face.

FIGURE 22. TEST 442 BARRIER LATERAL DISPLACEMENT

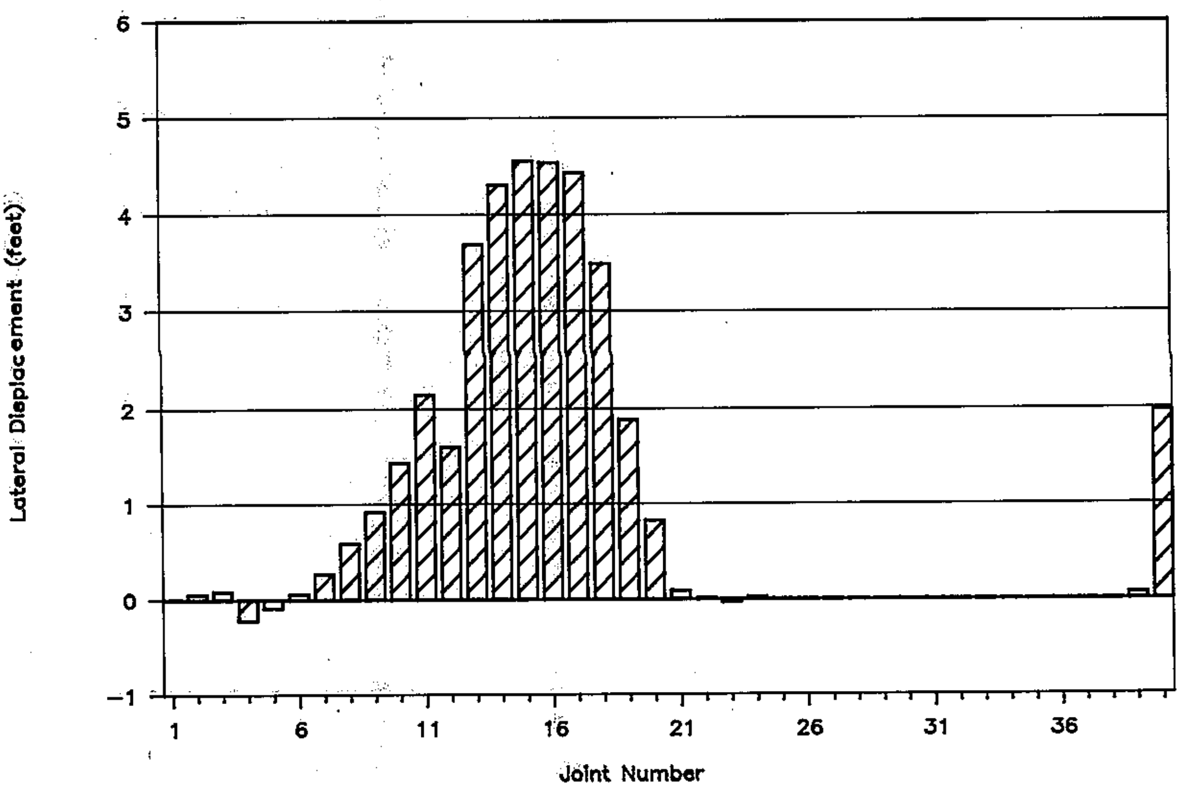


Lateral Displacement at
Main Impact Point



Lateral Displacement at
Second Car Impact.

FIGURE 23. TEST 442 BARRIER JOINT LATERAL DISPLACEMENT DIAGRAM



6.2.2.4. Dummy's Response - 442

During the impact the unrestrained dummy was thrown around the car and plunged partially through the left window twice. The portion of the dummy outside the car made no contact with the barrier. Then the dummy came back to its original position and moved to the right toward the passenger seat. When the dummy came to rest, it was lying across the passenger seat with its legs wedged under the steering wheel (Figure 24).

6.2.3 Test 443-4370 lb (1982 kg)/59.3 mph (26.5 m/s)/24°

The planned test conditions were: 4370 lb (1982 kg)/60 mph (26.8 m/s)/25 degrees. The Data Summary Sheet and photos taken before and after impact are shown in Figures 25 through 31.

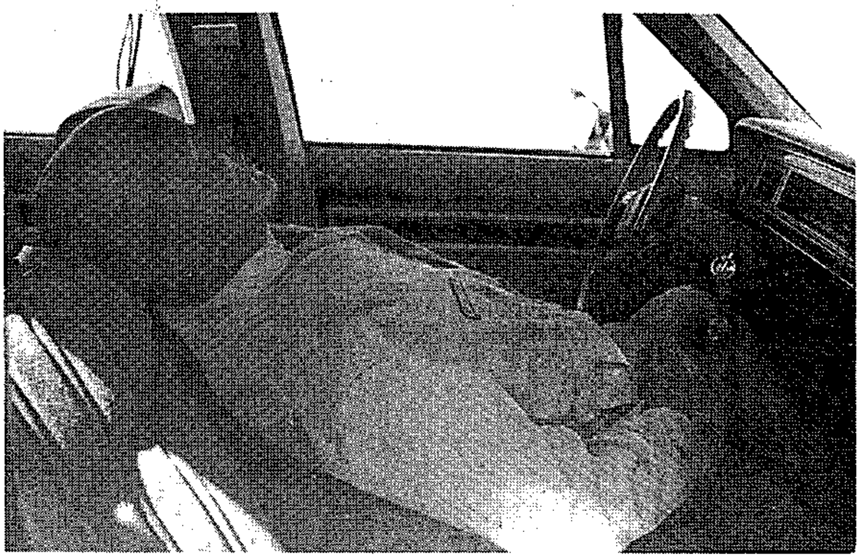
6.2.3.1 Impact Description - 443

The left front bumper of the test vehicle impacted the 100-segment barrier at midpoint of segment 62 as planned (Figure 26). The impact speed was 59.3 mph (26.5 m/s) at an angle of 24 degrees. The left front corner of the car contacted the barrier for a distance of about 26 feet (8 m). The left front tire rose to about 2.33 feet (0.7 m) above the ground on segment 62 and remained at that elevation for about 3 feet (1 m).

The length of vehicle contact with the barrier was about 39 feet (12 m) between segments number 62 and 74.

The car was smoothly redirected and lost contact with the barrier at an exit angle of 14-3/4 degrees. The vehicle remained upright during and after impact. During barrier impact, the car experienced a maximum negative roll of 10 1/4 degrees. The maximum rise of the car was 4 inches (0.1 m) 0.728 seconds after the impact measured at the right rear corner of the roof.

FIGURE 24. TEST 442 DUMMY'S FINAL POSITION



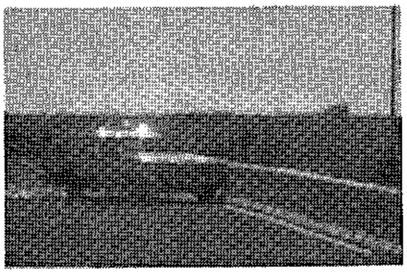
The postimpact trajectory of the car was back toward the line of the barrier. A second impact with the barrier occurred at segment 93. The car came to rest about 30 feet (9.1 m) beyond the downstream end of the barrier and approximately in line with its extended face (Figure 27).

The maximum 50 millisecond average accelerations were -7.7 g's in the lateral direction and -8.3 g's in the longitudinal direction. The longitudinal occupant impact velocity was 27 fps (8.22 m/s). The ridedown acceleration was -5.6 g's in the longitudinal direction and 7.6 g's in the lateral direction.

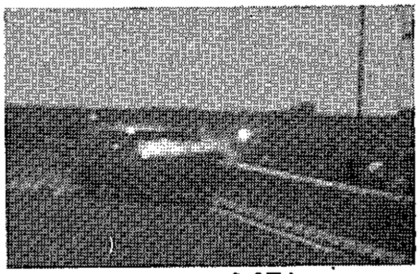
6.2.3.2 VEHICLE DAMAGE - 443

The first part of the vehicle to contact the barrier was the left side of the front bumper. Thus, immediately after impact, the left side of the bumper and the entire front fender including the left headlight were seriously damaged (Figure 28). The left side of the car was scraped and the door jammed. The bumper and grill were displaced 5 inches (0.13 m) and 3-1/2 inches (0.09 m)

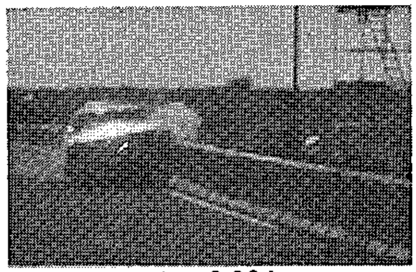
FIGURE 25 - DATA SUMMARY SHEET TEST 443



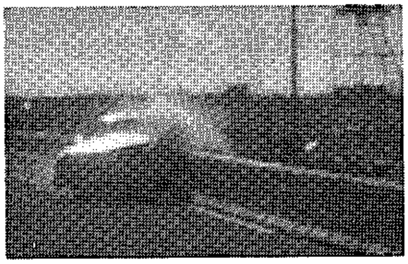
Impact + 0.014 s



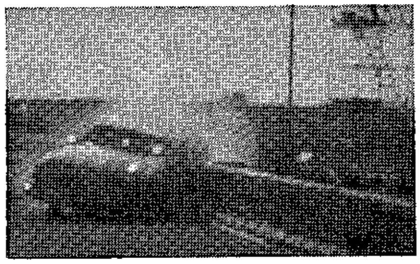
I + 0.074 s



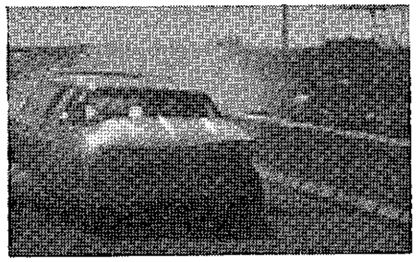
I + 0.204 s



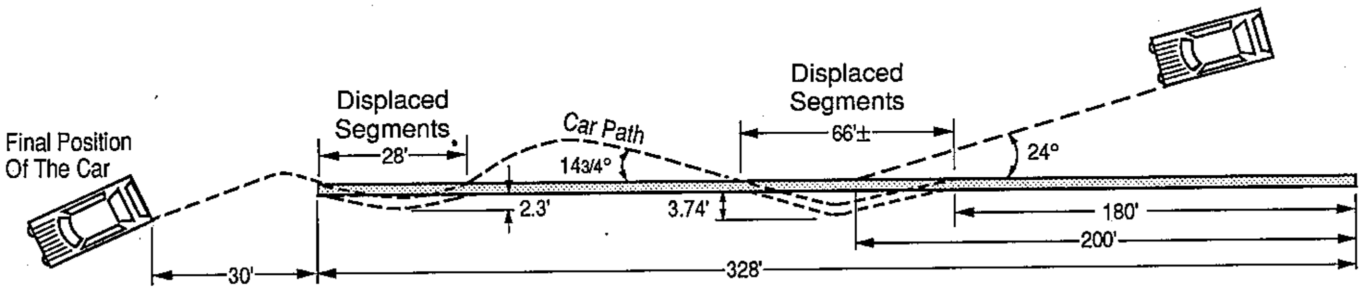
I + 0.674 s



I + 1.32 s



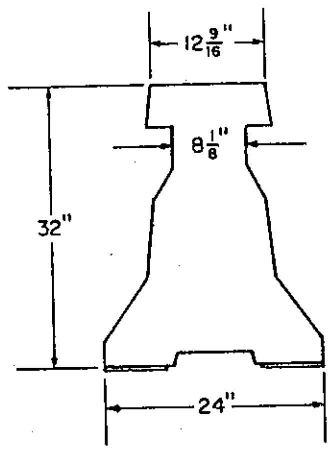
I + 1.68 s



1'=0.3048 m

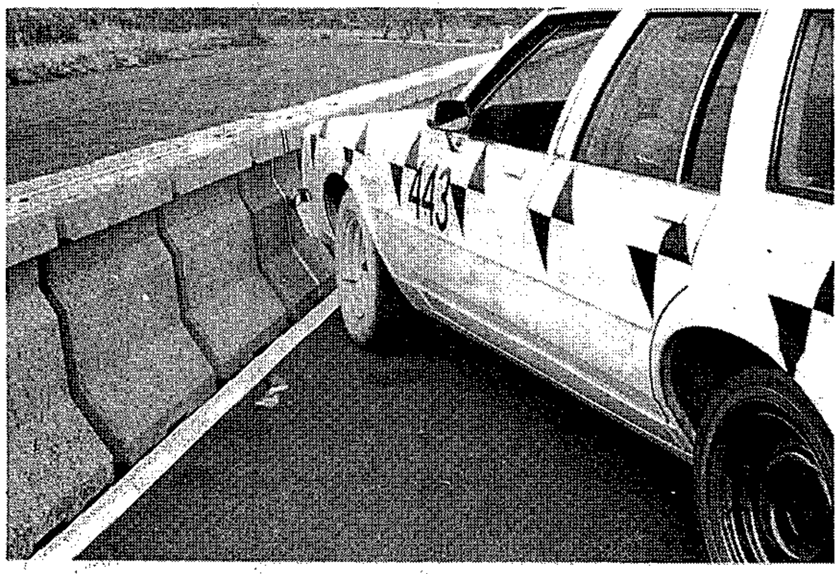
NOT TO SCALE

Test Barrier:
Type: Movable Concrete Barrier (Simple Hinge Connections with Reduced Clearance)
Length: 328 ft (100 m) - 100 segments
Test Date: November 18, 1987
TestVehicle:
Model: 1982 Olds Station Wagon
Inertial Mass: 4370 lb (1982 kg)
Impact Velocity: 59.3 mph (26.5 m/s)
Impact; Exit Angle: 24 deg; 14 3/4 deg
Test Dummy:
Type: Part 572, 50th Percentile Male
Weight / Restraint: 165 lb (75 kg)/ none
Position: Driver's seat
Test Data:
Occupant Impact Velocity (long): 27.0 fps. (8.2 m/s)
Max 50 ms Avg Accel: long –8.3 g, lat -7.7 g, vert -2.0 g
HIC / TAD / VDI: 121 / LFQ6 / 11LDEW2
Max Roll;Pitch;Yaw : –10 1/4 deg; NA; NA
Barrier Displacement: 3.74 ft (1.14 m) at segment 66
Max Dynamic Deflection (film): 4.10 ft (1.25m)
Barrier Damage: Minor scratches on 11 segments at the area of contact with test car

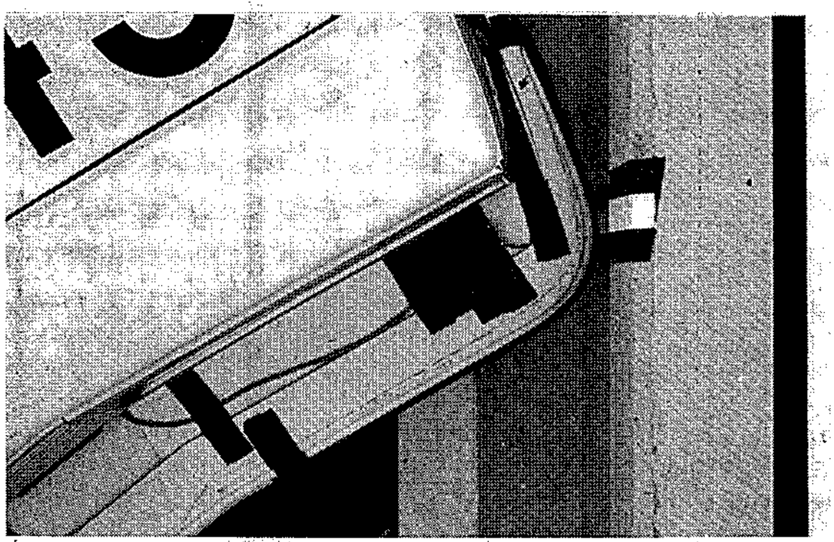


1"=0.0254 m

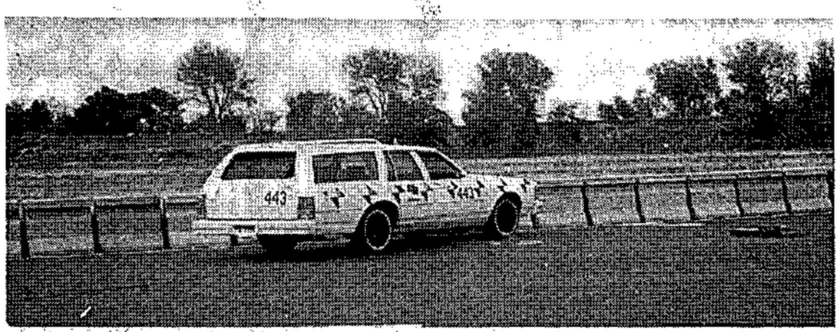
FIGURE 26. TEST 443 TEST VEHICLE AND BARRIER



1982 Olds Station Wagon 4370 (1982 kg) lb.



Planned Impact Point - Midpoint of Segment 62. Close-up View.



Planned Speed and Angle - 60 mph (26.8 m/s)/25 degrees.

FIGURE 27. TEST 443 FINAL LOCATION OF CAR

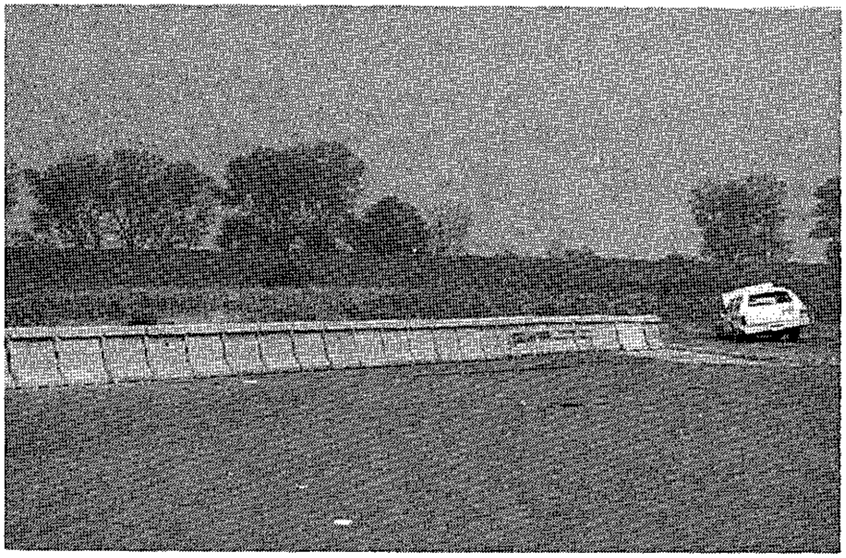
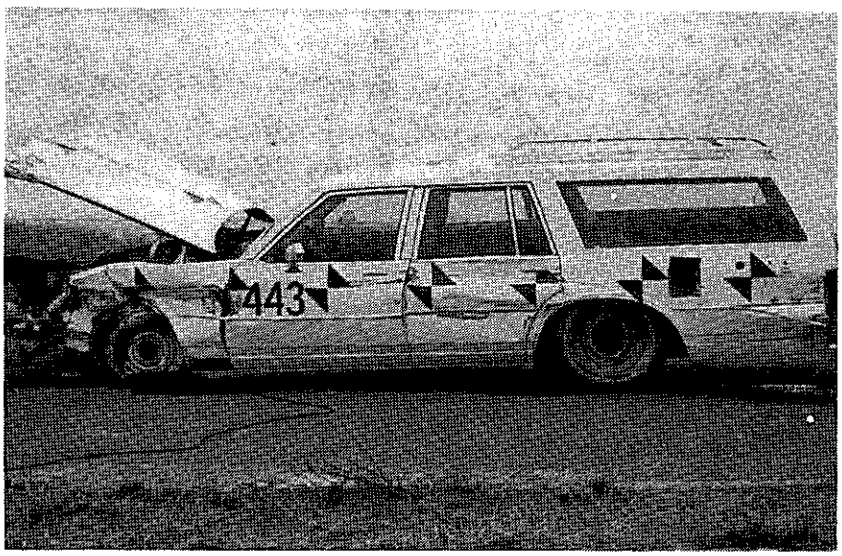


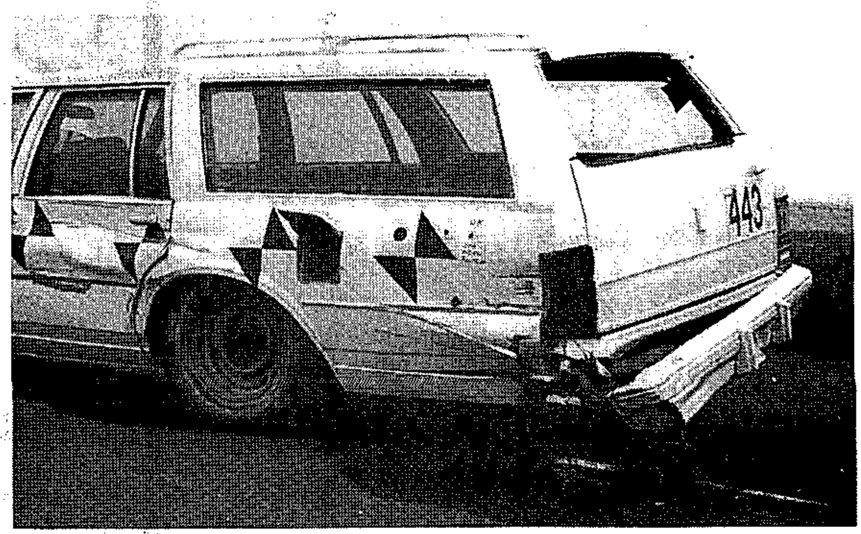
FIGURE 28. TEST 443 VEHICLE DAMAGE



Crushed Front Corner and Scrapes Along
Left Side of Car.

FIGURE 28 (Continued). TEST 443 VEHICLE DAMAGE

Severe Damage to Left Front Corner of Test Vehicle



Slight Damage to Rear Bumper

respectively, to the right. The left front rim was scraped and bent. The rear bumper was also slightly damaged. Both front tires were flattened, thus, restricting their movement.

There was no intrusion of vehicle or barrier parts into the passenger compartment during impact.

6.2.3.3. Barrier Damage - 443

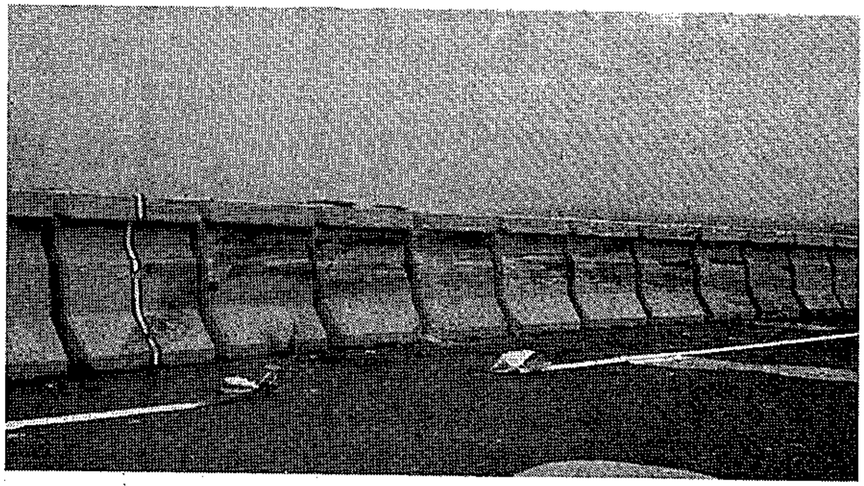
There was no evidence of any structural failure of the barrier. No visible cracks were detected. The only damage imparted to the barrier was (Figure 29) a few scrapes (segments 62 through 64, 68 through 71, 73, 95, 96, and 98), tire marks and minor spalling of (the bottom) corners of impacted concrete segments (segments 64, 65, 66).

The barrier was displaced laterally along a distance of about 66 feet (20 m) (segment 54 through 75). The maximum lateral permanent displacement was 3.74-feet (1.14 m) at segment 66 (Figure 30 and 31). Longitudinal movement of the barrier was observed and measured. The maximum longitudinal displacement in the downstream direction was 0.5-feet (0.15 m) at segment 54. The longitudinal displacement in the upstream direction was influenced by both the primary and secondary impact areas between segment 75 and the downstream end of the barrier. Its maximum value near the primary impact area was 0.15-feet (0.05 m) at segment 75.

6.2.3.4. Dummy's Response - 443

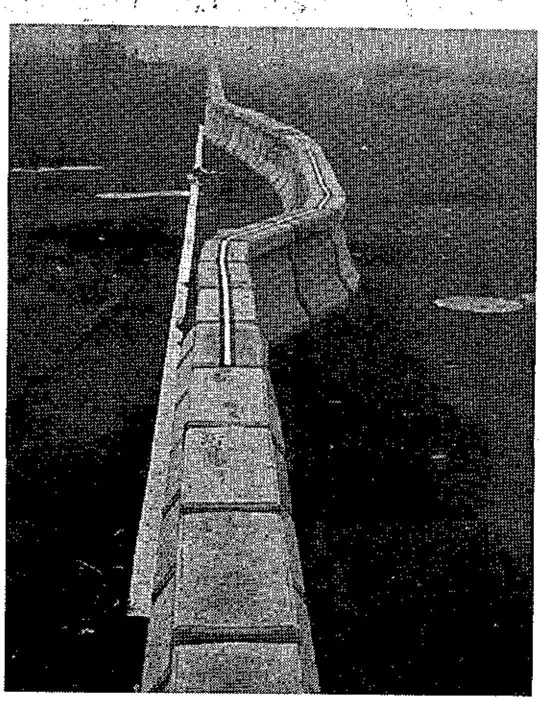
During the impact the unrestrained dummy hit the left front door twice and plunged its head briefly through the left window. Then the dummy came back to its original position and rolled forcefully to the right toward the passenger seat. When the dummy came to rest, it was laying on its right side across the passenger seat with its legs wedged under the steering wheel (Figure 32).

FIGURE 29. TEST 443 BARRIER DAMAGE



Tire Scuff Marks on Barrier Face; Minor Spalling at Bottom Corners of Concrete Segments.

FIGURE 30. TEST 443 BARRIER LATERAL DEFLECTION



Barrier Deflection at Primary Impact Zone.

Barrier Deflection at Secondary Impact Zone.

FIGURE 31. TEST 443 BARRIER JOINT LATERAL DEFLECTION DIAGRAM

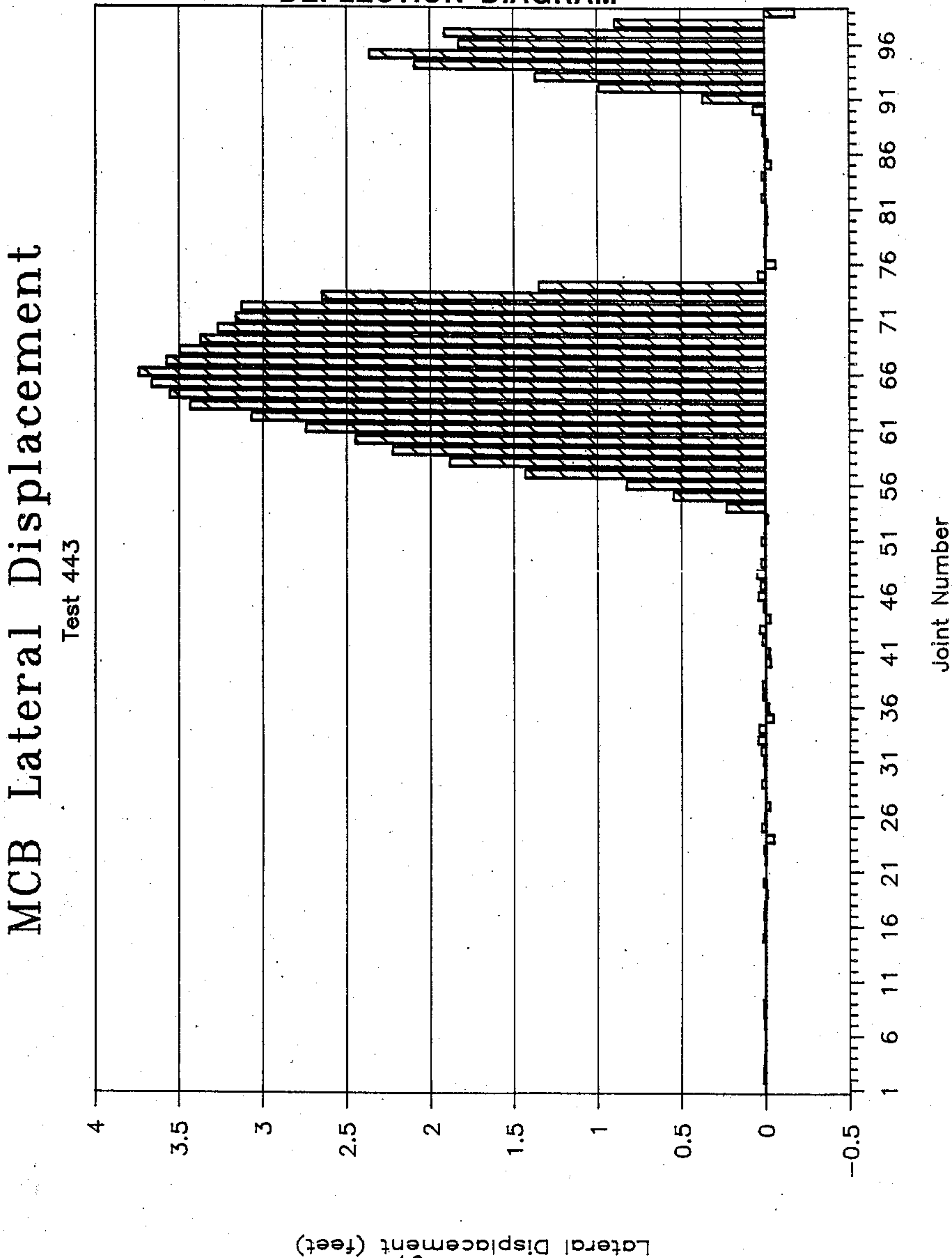


FIGURE 32. TEST 443 DUMMY'S FINAL POSITION

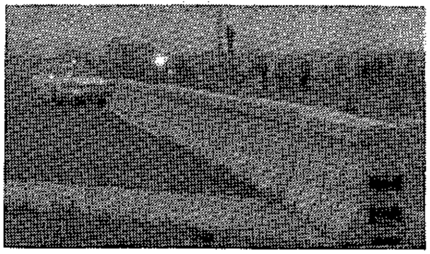
6.2.4 Test 444-2000 lb (907 kg)/57.7 mph (25.8 m/s)/15-1/2°

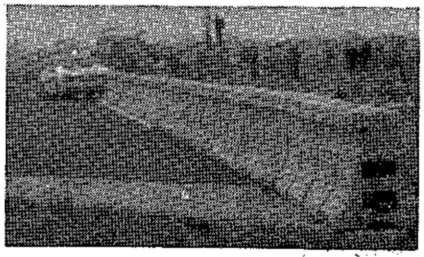
The planned test conditions were: 2000 lb (907 kg)/60 mph (26.8 m/s)/15 degrees. The Data Summary Sheet and photos taken before and after impact are shown in Figures 33 through 39.

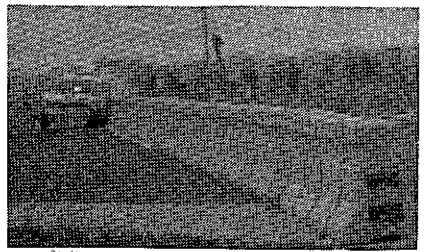
6.2.4.1. Impact Description - 444

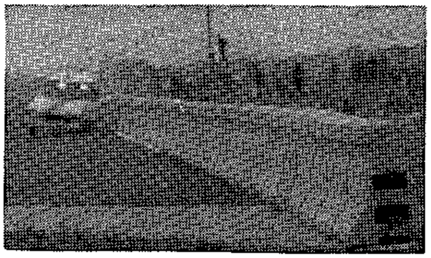
The left front bumper of the test vehicle impacted the 100 segment barrier at segment 48 as planned (Figure 34). The impact speed was 57.7 mph (25.8 m/s) at an angle of 15-1/2 degrees. The left front corner of the car contacted the barrier for a distance of about 10-feet (3 m). The left front tire rose to about 1-foot (0.3 m) above the ground on segment 49 and remained at that elevation for about 3.3-feet (1 m). The left rear tire initially contacted the barrier at segment 50 and remained in contact with the barrier at ground level through segment 52. The length of vehicle contact with the barrier was about 16 feet (5 m) between segments number 48 and 52. The car was smoothly redirected and lost contact with the barrier at an exit angle of 10-1/4 degrees. The vehicle remained upright during and after impact.

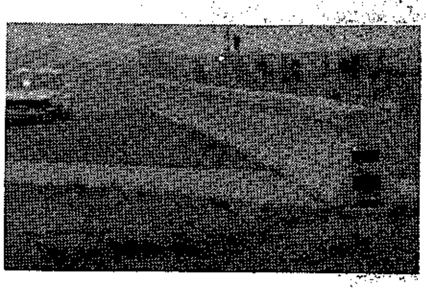
FIGURE 33 - DATA SUMMARY SHEET TEST 444

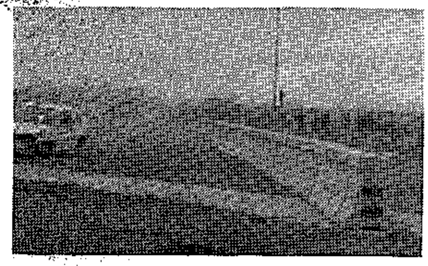

Impact + 0.054 s

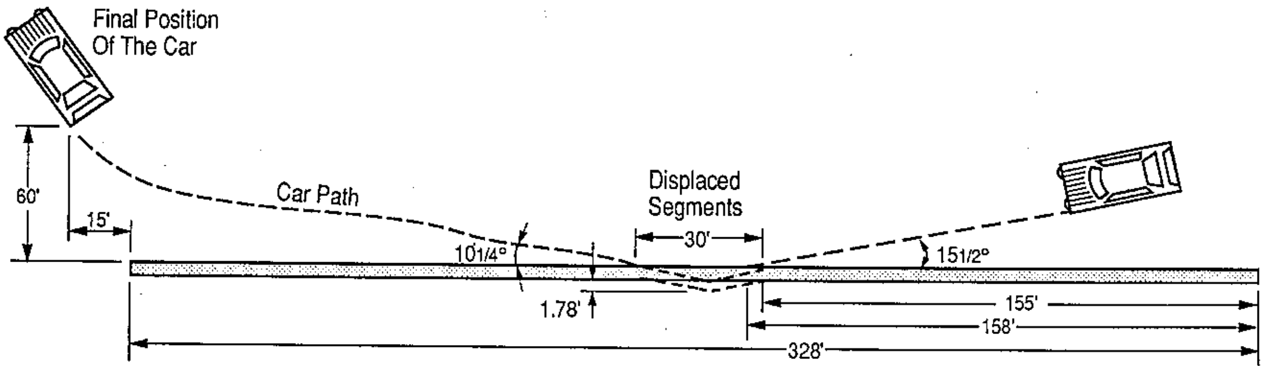

I + 0.209 s


I + 0.401 s


I + 0.591 s


I + 1.288 s


I + 2.322 s



1'=0.3048 m NOT TO SCALE

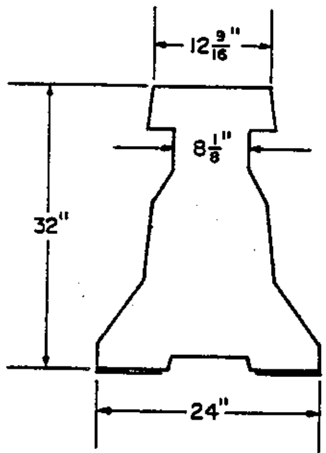
Test Barrier:
- Type: Movable Concrete Barrier (Simple Hinge Connections with Reduced Clearance)
- Length: 328 ft (100 m) - 100 segments

Test Date: December 18, 1987

TestVehicle:
- Model: 1981 Honda Civic
- Inertial Mass: 2000 lb (907 kg)
- Impact Velocity: 57.7 mph (25.8 m/s)
- Impact; Exit Angle: 15 1/2 deg; 10 1/4 deg

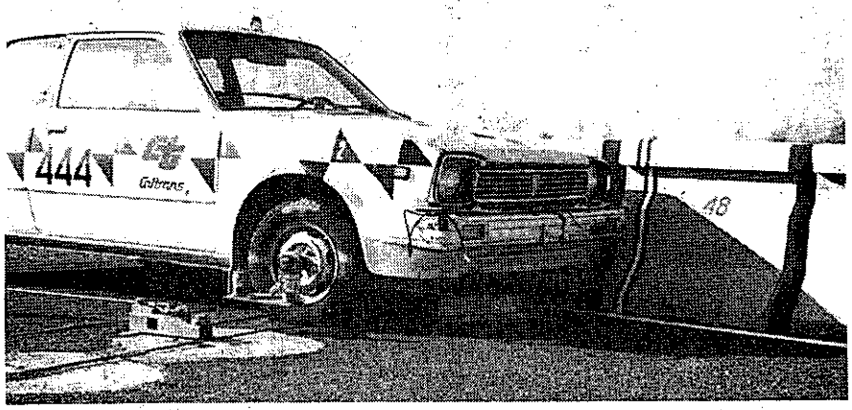
Test Dummy:
- Type: Part 572, 50th Percentile Male
- Weight / Restraint: 165 lb (75 kg)/ none
- Position: Driver's seat

Test Data:
- Occupant Impact Velocity (long): 15.1 fps. (4.6 m/s)
- Max 50 ms Avg Accel: long –4.6 g, lat –6.7 g, vert 1.7 g
- HIC / TAD / VDI: 30 / LFQ4 / 12LDEE2
- Max Roll;Pitch;Yaw : –14 1/2 deg; 10 1/4 deg; NA
- Barrier Displacement: 1.78 ft (0.54 m) at segment 51
- Max Dynamic Deflection (film): 1.92 ft (0.58 m)
- Barrier Damage: Minor scratches at the area of contact with test car



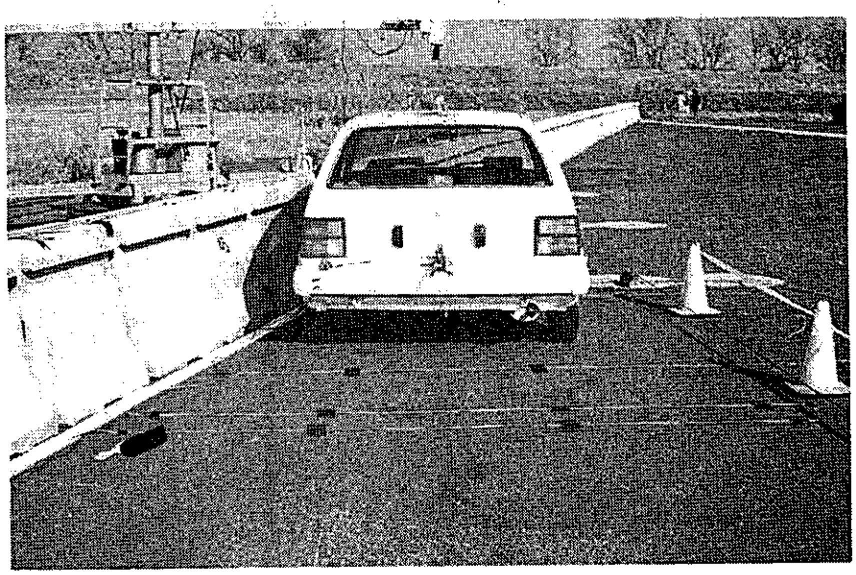
1"=0.0254 m

FIGURE 34. TEST 444 TEST VEHICLE AND BARRIER



1981 Honda Civic, 2000 lb (907 kg) at Planned Point of Impact.

Planned Impact Point - Close to Upstream End of Segment 48. Close-up view.



Planned Impact Speed and Angle - 60 mph (26.8 m/s)/ 25 degrees.

During barrier impact, the car experienced a maximum negative roll of 14-1/2 degrees and a positive pitch of 10-1/4 degrees. The maximum rise of the car was 17 inches (0.4 m) 0.36 seconds after the impact, measured on the right rear tire.

The postimpact trajectory of the car was away from the barrier. The car came to rest off the paved area about 15 feet (4.6 m) beyond the downstream end of the barrier and 60 feet (18.3 m) from its face (Figure 35).

The maximum 50 millisecond average accelerations were -6.7 g's in the lateral direction and -4.6 g's in the longitudinal direction. The longitudinal occupant impact velocity was 15.1 fps (4.6 m/s). The ridedown accelerations were less than 15 g's in both the longitudinal and lateral directions.

6.2.4.2. Vehicle Damage - 444

The first part of the vehicle to contact the barrier was the left side of the front bumper. Thus, immediately after impact, the left side of the bumper and the entire front fender including the left headlight were seriously damaged (Figure 36). The left side of the car was scraped and crinkled. The left, front door was scraped, crinkled, jammed and partially opened. The left side of the hood was jammed and the hood could not be opened. The radiator was intact but the engine was moved to the right. The left front tire was flattened and its movement restricted.

There was no intrusion of vehicle or barrier parts into the passenger compartment during impact.

6.2.4.3. Barrier Damage - 444

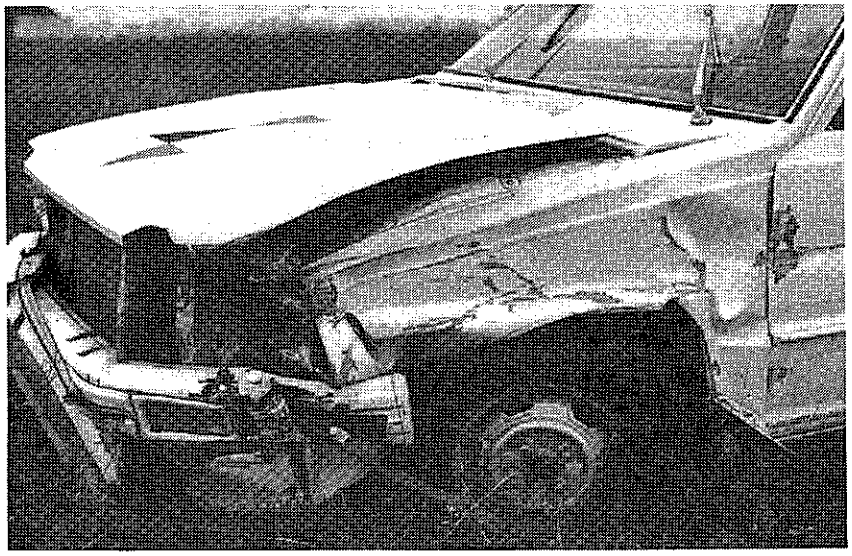
There was no evidence of any structural failure of the barrier. No visible cracks were detected. The only damage imparted to the barrier was a few scrapes and tire marks (Figure 37).

FIGURE 35. TEST 444 FINAL LOCATION OF CAR

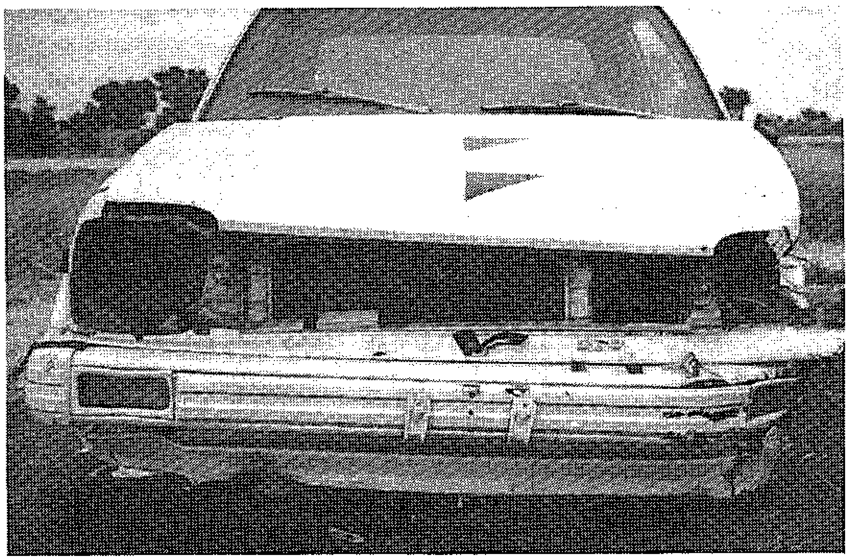
FIGURE 36. TEST 444 VEHICLE DAMAGE

Damage to Left Front Side of Test Car.

FIGURE 36 (Continued). TEST 444 VEHICLE DAMAGE



Crushed Left Front Corner and Flat Left Front Tire



Front View of Damaged Car. Engine Moved to the Right.

The barrier was displaced laterally along a distance of about 30 feet (9.1 m) (segments 46 through 55). The maximum lateral permanent displacement was 1.78 feet (0.54 m) at segment 51 (Figure 38 and 39).

There was longitudinal movement in the barrier from segment 36 to 65. The maximum longitudinal displacement in the downstream direction was 0.1-foot (0.03 m) at segment 47. The maximum longitudinal displacement in the upstream direction was 0.1-foot (0.03 m) at segment 55.

6.2.4.4. Dummy's Response - 444

During the impact the unrestrained dummy hit the left front door and plunged its head briefly through the left window. Then the dummy returned to its original position where it remained until the car came to rest.

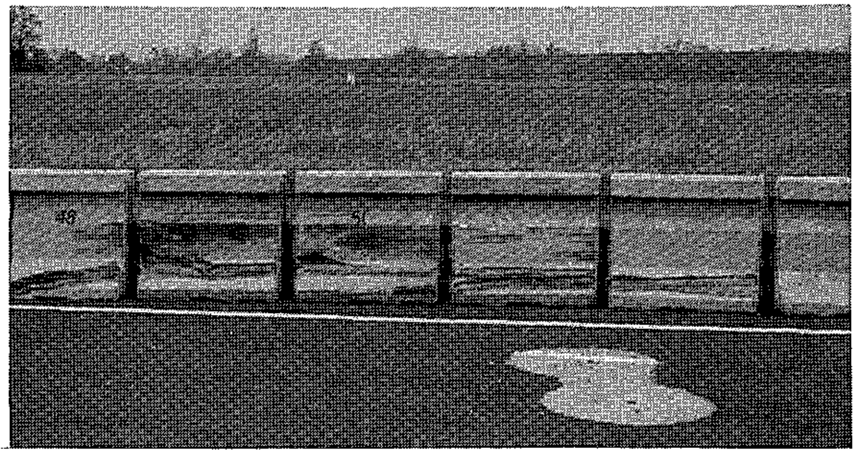
6.2.5 Test 445-4300 lb (1950 kg)/59.4 mph (26.6 m/s)/16°

The planned test conditions were: 4300 lb (1950 kg)/60 mph (26.8 m/s)/15 degrees. The Data Summary Sheet and photos taken before and after impact are shown in Figures 40 through 47.

6.2.5.1. Impact Description - 445

The left front bumper of the test vehicle impacted the 100-segment barrier at midpoint of segment 52, two segments off from the planned segment 50 (Figure 41). The impact speed was 59.4 mph (26.6 m/s) at an angle of 16 degrees. The left front corner of the car contacted the barrier for a distance of about 19.7 feet (6 m). The left front tire rose to about 1.2 feet (0.4 m) above the ground on segment 54 and remained at that elevation for about 13 feet (4 m). The left rear tire initially contacted the barrier at segment 58 and rose about 15 inches (0.4 m) above the ground at segment 59. The length of vehicle contact with the barrier was about 33 feet (10 m) between segments 52 and 61. The car was smoothly redirected and lost contact with the barrier at an exit angle of 16-1/2 degrees. The vehicle remained upright during and after impact.

FIGURE 37. TEST 444 BARRIER DAMAGE



Tire Scuffs on Barrier Face

FIGURE 38. TEST 444 BARRIER LATERAL DEFLECTION

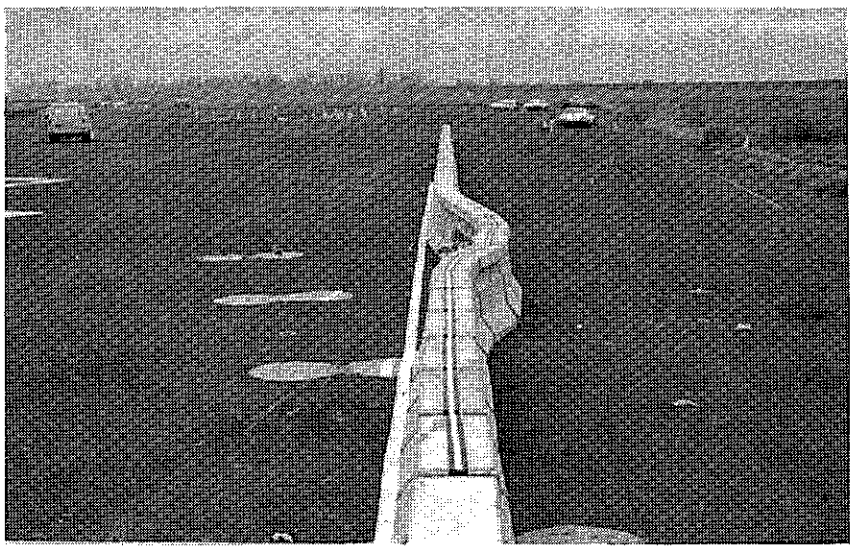


FIGURE 39. TEST 444 BARRIER JOINT LATERAL DEFLECTION DIAGRAM

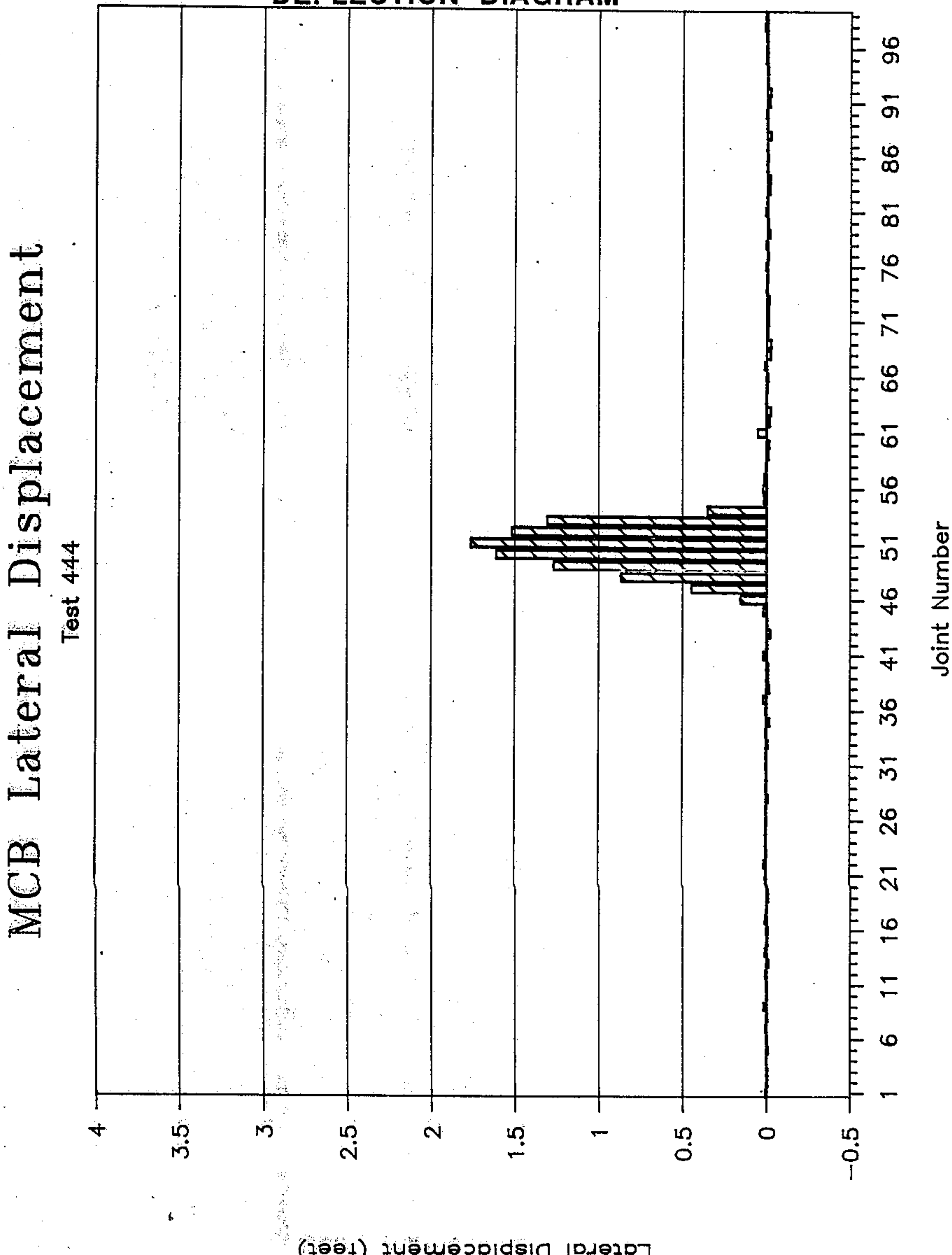
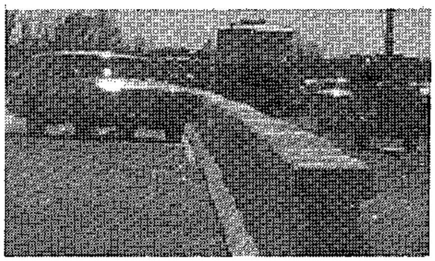
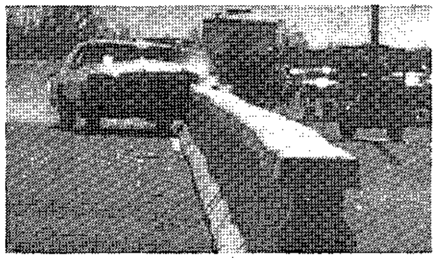
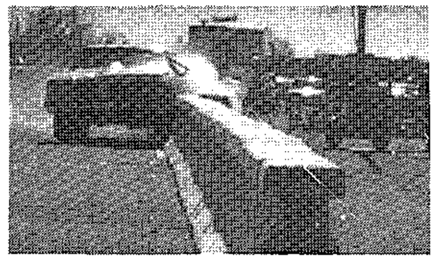
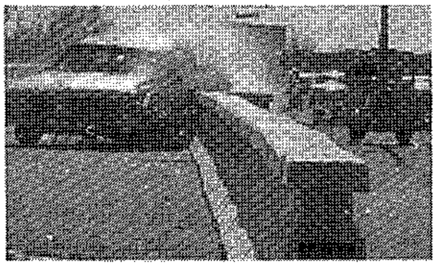


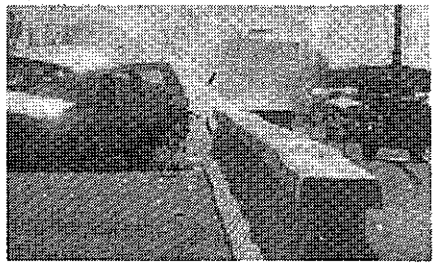
FIGURE 40 - DATA SUMMARY SHEET TEST 445

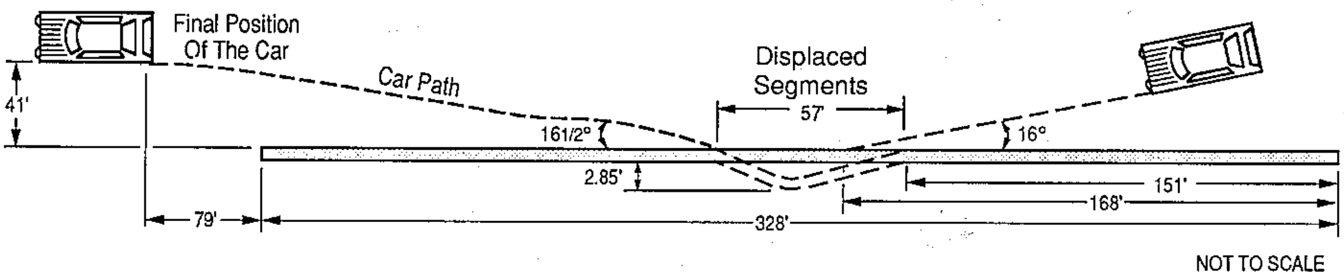

Impact


I + 0.118 s


I + 0.238 s


I + 0.458 s


I + 0.71 s



1'=0.3048m

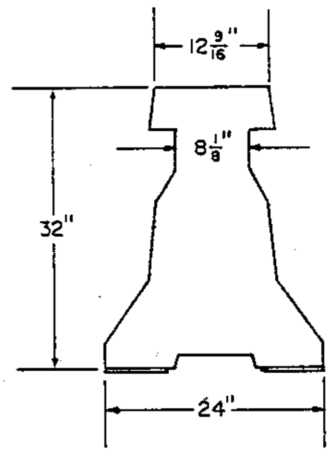
Test Barrier:
- Type: Movable Concrete Barrier (Simple Hinge Connections with Reduced Clearance)
- Length: 328 ft (100 m) - 100 segments

Test Date: January 21, 1988

TestVehicle:
- Model: 1982 Olds Station Wagon
- Inertial Mass: 4300 lb (1950 kg)
- Impact Velocity: 59.4 mph (26.6 m/s)
- Impact; Exit Angle: 16 deg; 16 1/2 deg

Test Dummy:
- Type: Part 572, 50th Percentile Male
- Weight / Restraint: 165 lb (75 kg)/ none
- Position: Driver's seat

Test Data:
- Occupant Impact Velocity (long): 14.3 fps (4.4 m/s)
- Max 50 ms Avg Accel: long –3.3 g, lat –5.9 g, vert –1.7 g
- HIC / TAD / VDI: 45 / LFQ4 / 12LDEE2
- Max Roll;Pitch;Yaw : 6 1/4 deg; 5 3/8 deg; NA
- Barrier Displacement: 2.85 ft (0.87 m) at segment 59
- Max Dynamic Deflection (film): 3.04 ft (0.93 m)
- Barrier Damage: Minor scratches and spalling at the area of contact with test car



1"=0.0254m

FIGURE 41. TEST 445 TEST VEHICLE AND BARRIER

1982 Olds Station Wagon, 4300 lb (1950 kg) at Planned Point of Impact.

Planned Impact Point: Midpoint of Segment 50.

Planned Impact Speed and Angle - 60 mph (26.8 m/s)/15°.

During barrier impact, the car experienced a maximum positive roll of 6-1/4 degrees and a positive pitch of 5-3/8 degrees. The maximum rise of the car was 19 inches (0.5 m) 0.55 seconds after the impact, measured on the right rear bumper.

The postimpact trajectory of the car was away from the barrier. The car came to rest off the paved area at the toe of the earth berm about 79-feet (24 m) beyond the downstream end of the barrier and 41-feet (12.5 m) from its face (Figure 42).

The maximum 50 millisecond average accelerations were -5.9 g's in the lateral direction and -3.3 g's in the longitudinal direction. The longitudinal occupant impact velocity was 14.3 fps (4.4 m/s). The ridedown acceleration was -3.9 g's in the longitudinal direction and 10.6 g's in the lateral direction.

6.2.5.2. Vehicle Damage - 445

The first part on the vehicle to contact the barrier was the left side of the front bumper. Thus, immediately after impact, the left side of the bumper and the entire front fender including the left headlight were seriously damaged (Figure 43). The left side of the car was scraped and crinkled. The left doors were crushed and jammed. The left front door post was deformed as a result of the door damage. The hood was displaced to the left and could not be opened. The radiator and the engine were intact and unmoved. Both left tires were flattened and their movement was restricted.

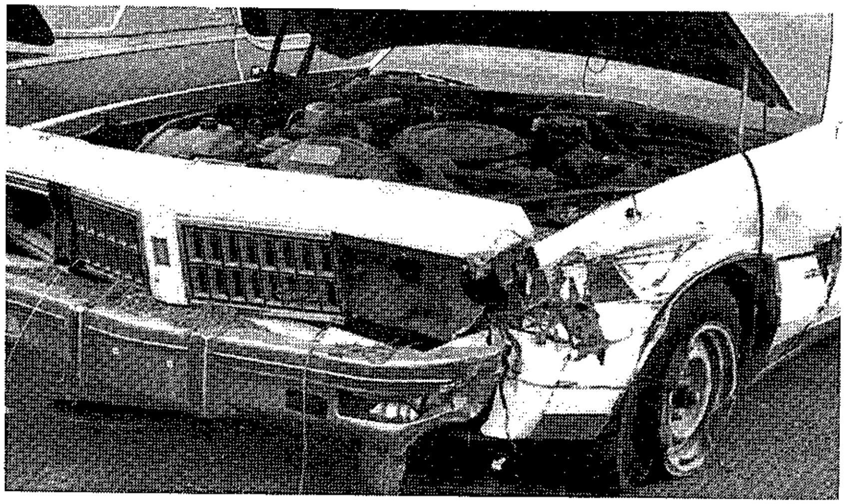
There was no intrusion of vehicle or barrier parts into the passenger compartment during impact.

FIGURE 42. TEST 445 FINAL LOCATION OF CAR

FIGURE 43. TEST 445 VEHICLE DAMAGE

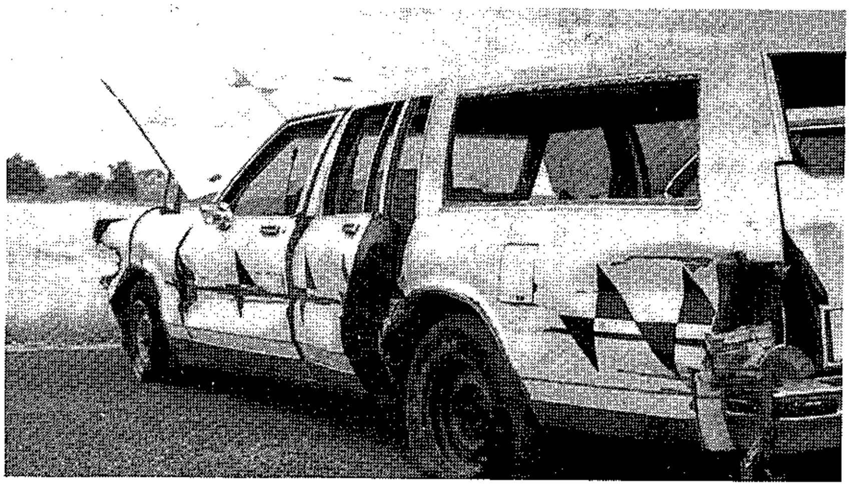
Damage to Left Side of Car.

FIGURE 43 (Continued). TEST 445 VEHICLE DAMAGE



Severely Damaged Left Front Corner of Car.

Close-up View of Left Front Corner.



Scrapes and Crinkles on Left Side of Car. Both Left Tires are Flat.

6.2.5.3. Barrier Damage - 445

There was no evidence of any structural failure of the barrier. No visible cracks were detected. The only damage imparted to the barrier was minor spalling characterized by insignificant damage to the surface and corners (Figure 44). A few scrapes and tire marks were also observed . Some debris was found in an area of 150 x 200 feet (46 x 61 m) close to the impact point.

The barrier was displaced laterally along a distance of about 59-feet (18 m) (segments 47 through 65). The maximum lateral permanent displacement was 2.85-feet (0.9 m) at segment 59 (Figures 45 and 46).

There was longitudinal movement in the barrier from segment 25 to 81. The maximum longitudinal displacement in the downstream direction was 0.4-feet (0.1 m) at segment 58. The maximum longitudinal displacement in the upstream direction was 0.1-feet (0.03 m) at segment 70.

6.2.5.4. Dummy's Response - 445

During the impact the unrestrained dummy hit the left front door then returned to its original position. The dummy continued to move to the right toward the passenger seat.

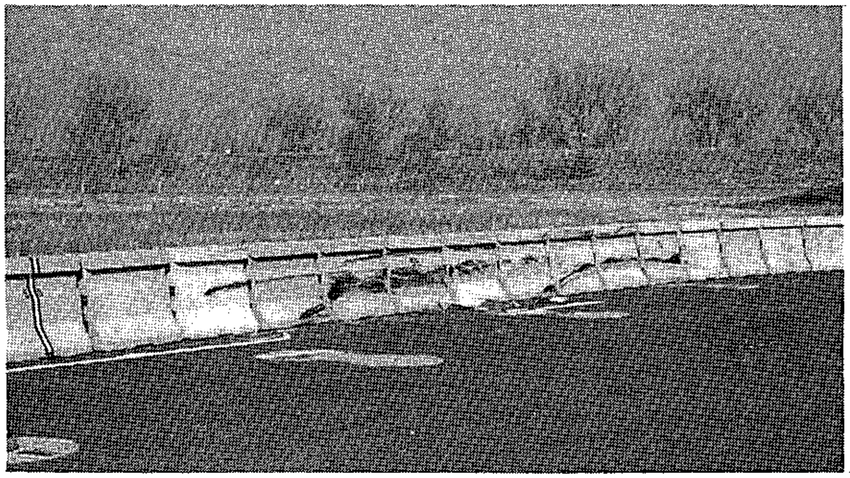
When the dummy came to rest, it was laying face down in front of the passenger seat with its legs wedged under the steering wheel (Figure 47).

6.2.6. Test 446-1890 lb (857 kg)/58.6 mph (26.2 m/s)/20-1/2°

The planned test conditions were: 1800 lb (816 kg)/60 mph (26.8 m/s)/20 degrees. This was a supplementary test which was designed to conform to potential future crash test standards.

The Data Summary Sheet and photos taken before and after impact are shown in Figures 48 through 55.

FIGURE 44. TEST 445 BARRIER DAMAGE



Tire Scuffs and Scrapes on Barrier Face.

FIGURE 45. TEST 445 BARRIER LATERAL DISPLACEMENT

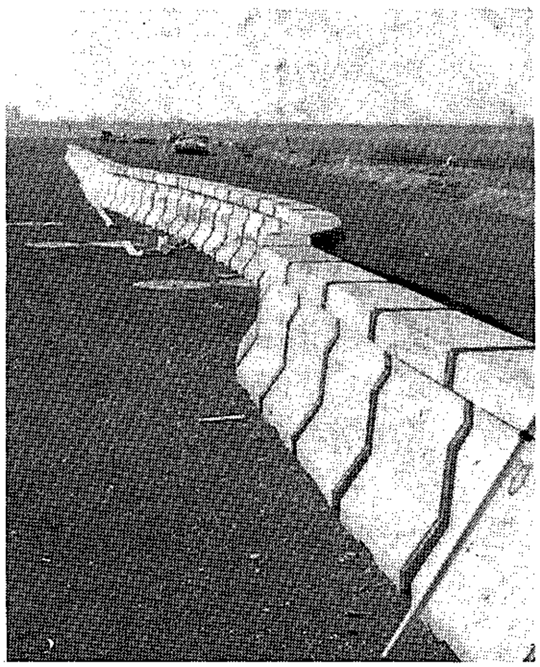


FIGURE 46.
TEST 445 BARRIER JOINT LATERAL DEFLECTION DIAGRAM

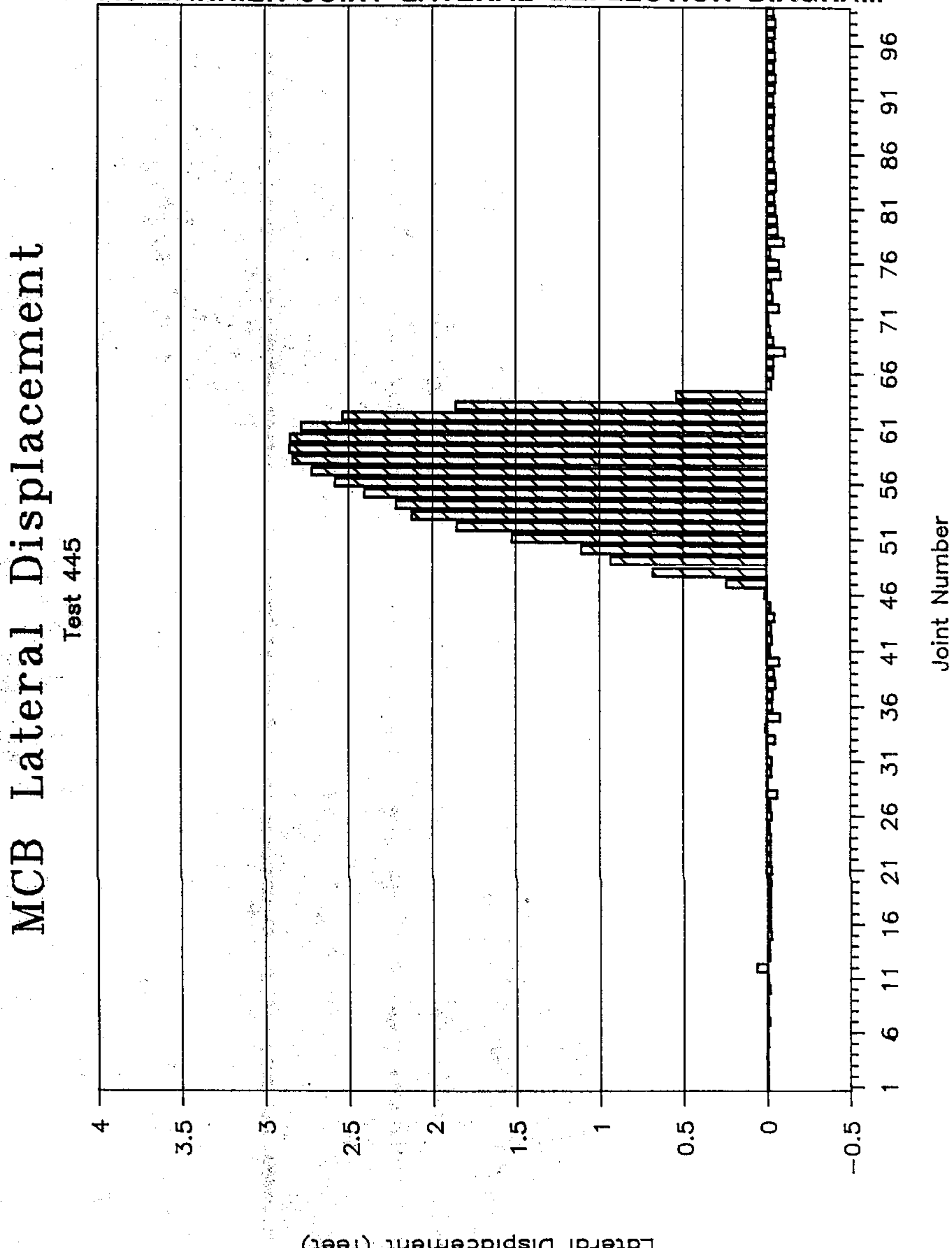
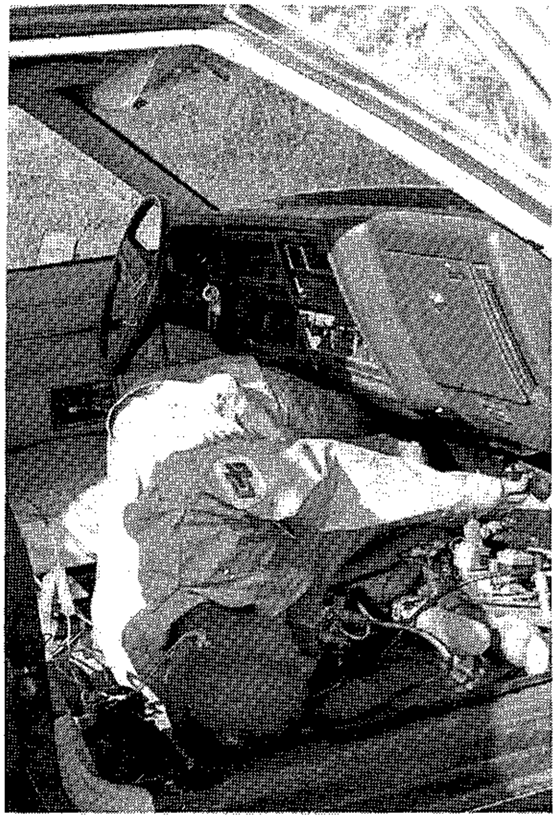


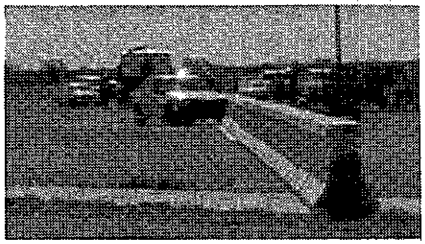
FIGURE 47. TEST 445 DUMMY'S FINAL POSITION



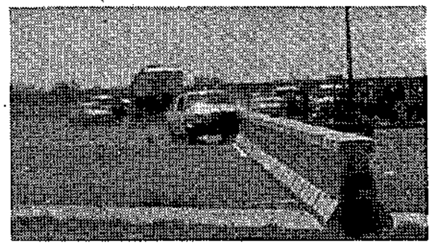
6.2.6.1 Impact Description - 446

The left front bumper of the test vehicle impacted the 100-segment barrier at segment 55 (Figure 49). The impact speed was 58.6 mph (26.2 m/s) at an angle of 20-1/2 degrees. The left front corner of the car contacted the barrier for a distance of about 11-feet (3.4 m). The left front tire rose to about 2-feet (0.6 m) above the ground on segment 56 and remained at that elevation for about 7 feet (2.1 m). The left rear tire initially contacted the barrier at segment 58 and rose about 20-inches (0.5 m) above the ground at segment 59. The length of vehicle contact with the barrier was about 20-feet (6 m) between

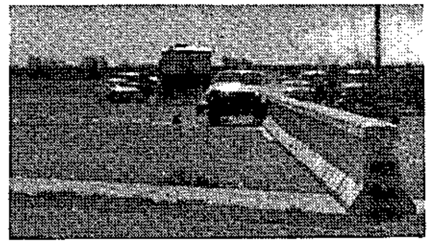
FIGURE 48 - DATA SUMMARY SHEET TEST 446



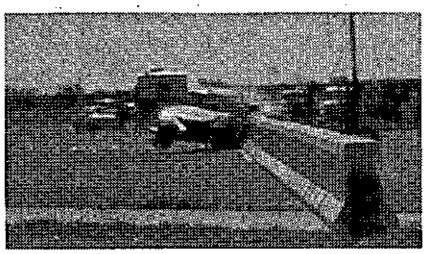
Impact + 0.015 s



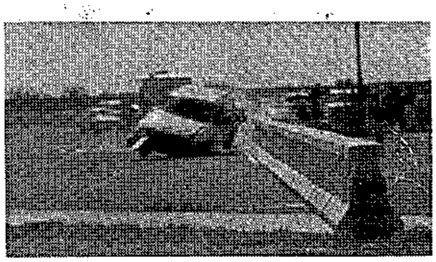
I + 0.098 s



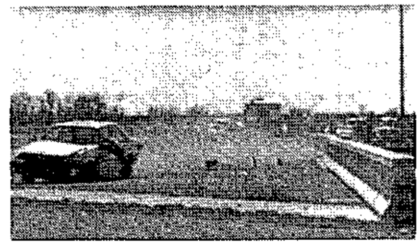
I + 0.168 s



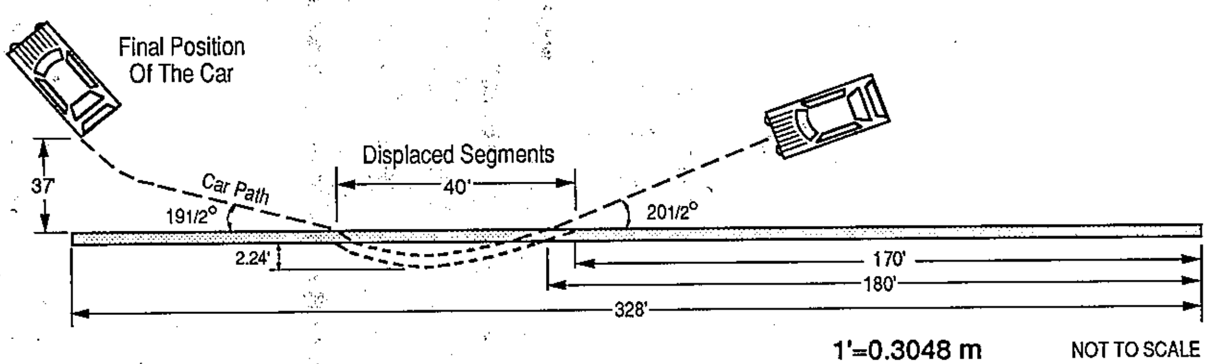
I + 0.303 s



I + 0.515 s



I + 1.208 s



Test Barrier:
- Type: Movable Concrete Barrier (Simple Hinge Connections with Reduced Clearance)
- Length: 328 ft (100 m) - 100 segments

Test Date: March 9, 1988

TestVehicle:
- Model: 1984 Nissan
- Inertial Mass: 1890 lb (857 kg)
- Impact Velocity: 58.6 mph (26.2 m/s)
- Impact; Exit Angle: 201/2 deg; 191/2 deg

Test Dummy:
- Type: Part 572, 50th Percentile Male
- Weight / Restraint: 165 lb (75 kg)/ none
- Position: Driver's seat

Test Data:
- Occupant Impact Velocity (long): 16.9 fps (5.2 m/s)
- Max 50 ms Avg Accel: long -7.6 g, lat –11.3 g, vert 2.8g
- HIC / TAD / VDI: 86 / LFQ4 / 11LDEE2
- Max Roll;Pitch;Yaw : –15 deg; 121/2 deg; NA
- Barrier Displacement: 2.24 ft (0.68 m) at segment 59
- Max Dynamic Deflection (film): 2.41 ft (0.73 m)
- Barrier Damage: Minor scratches on 2 segments at the area of contact with test car

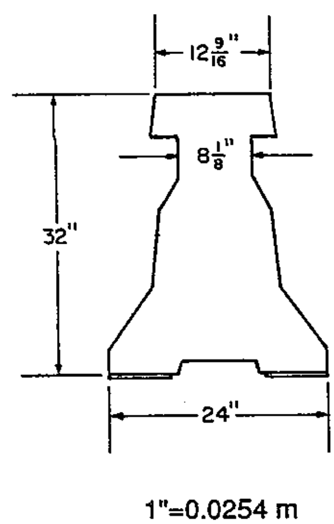
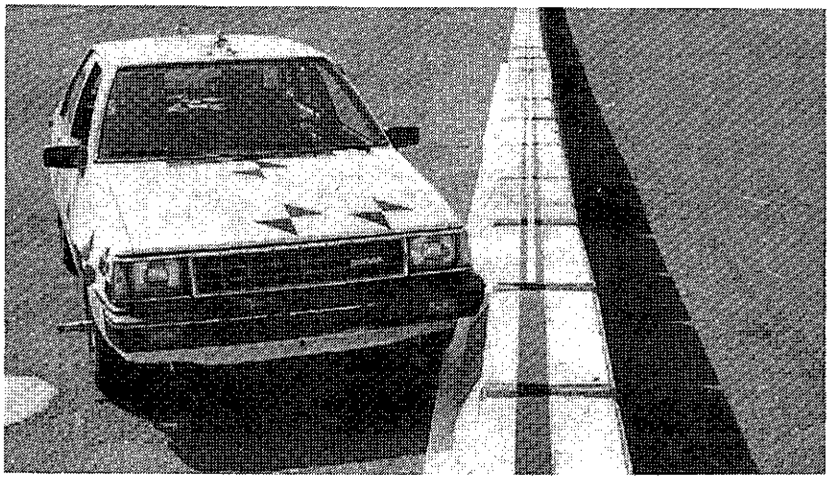
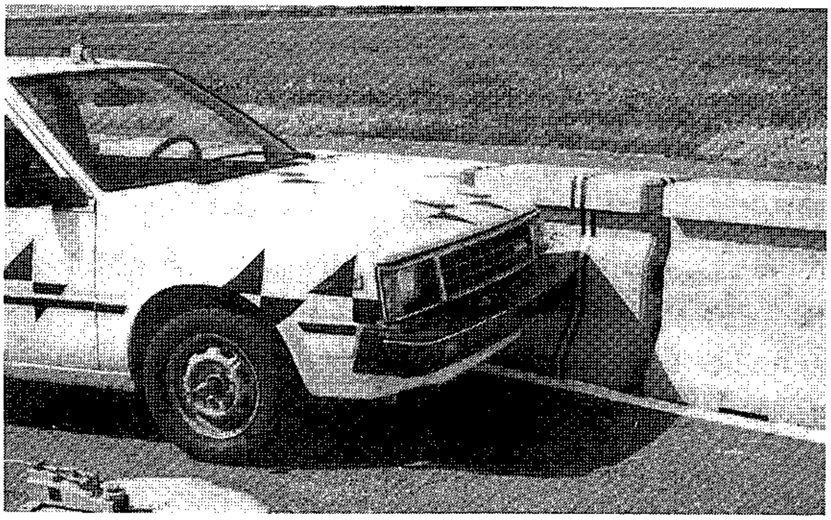


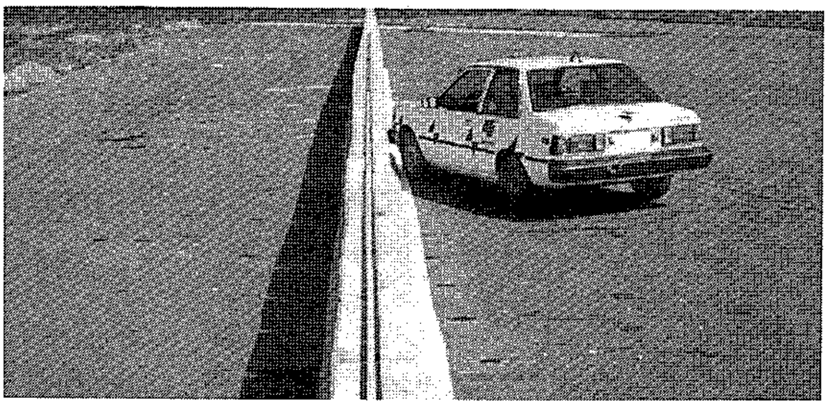
FIGURE 49. TEST 446 TEST VEHICLE AND BARRIER



1984 Nissan Sentra 1890 lb (857 kg) at Planned Point of Impact.



Planned Impact Point - Segment 55.



Planned Impact Speed and Angle - 60 mph (26.8 m/s)/20 degrees.

segments 55 and 60. The car was smoothly redirected and lost contact with the barrier at an exit angle of 19-1/2 degrees. The vehicle remained upright during and after impact.

During impact, the car experienced a maximum negative roll of 15 degrees and a positive pitch of 12-1/2 degrees. The maximum rise of the car was 30-inches (0.8 m) 0.44 seconds after the impact, measured on the right rear bumper.

The post impact trajectory of the car was away from the barrier. The car came to rest about even with the downstream end of the barrier 37-feet (11 m) away from its face (Figure 50).

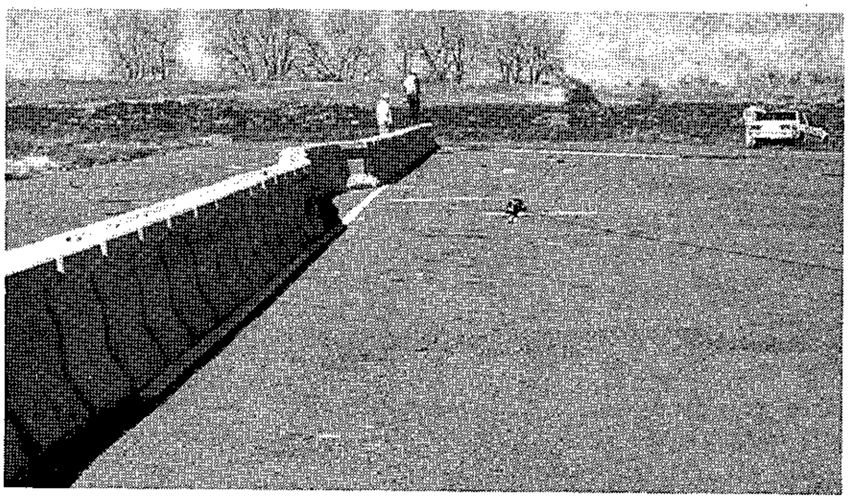
The maximum 50 millisecond average accelerations were -11.3 g's in the lateral direction and -7.6 g's in the longitudinal direction. The longitudinal occupant impact velocity was 16.9 fps (5.2 m/s). The ridedown accelerations were less than 15 g's in both longitudinal and lateral directions.

6.2.6.2. Vehicle Damage - 446

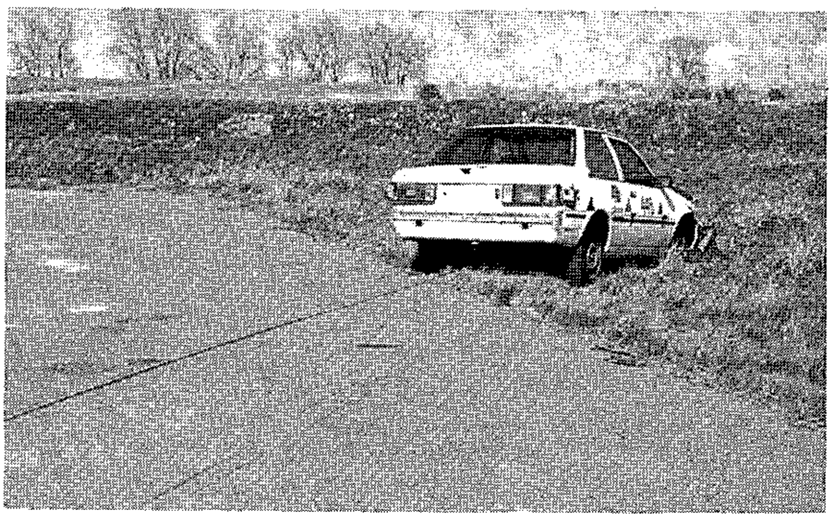
The first part of the vehicle to contact the barrier was the left side of the front bumper. Thus, immediately after impact, the left side of the bumper was damaged. The left headlight and taillight were broken. The left front fender was severely crushed and the left rear fender was crinkled (Figure 51). The left front door was crushed and jammed. It was bent outward at the bottom of the window by the dummy. The left front frame member under the engine was slightly bent. The hood was opened and its left front corner was crushed. The radiator was pushed back to the fan. Both left and right front tires were flattened and wheel movement was restricted.

There was no intrusion of vehicle or barrier parts into the passenger compartment during impact.

FIGURE 50. TEST 446 FINAL CAR POSITION



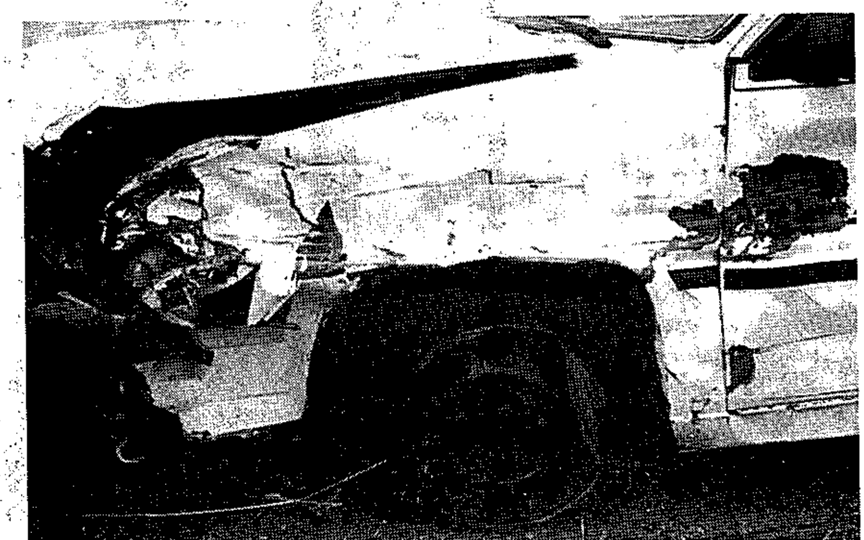
Postimpact Trajectory of the Car Away from Barrier.



Final Car Location.

FIGURE 51. TEST 446 VEHICLE DAMAGE

Damage to Car Left Side-Scrapes and Wrinkles.



Severely Crushed Left Front Side. Flat Left Front Tire.

Close-up View of Damaged Left Front Corner.

6.2.6.3. Barrier Damage - 446

There was no evidence of any structural failure of the barrier. No visible cracks were detected. The only damage imparted to the barrier was a few scrapes and tire marks (Figure 52).

The barrier was displaced laterally along a distance of about 42-feet (13 m) (segments 52 through 64). The maximum lateral permanent displacement was 2.24-feet (0.68 m) at segment 59 (Figures 53 and 54).

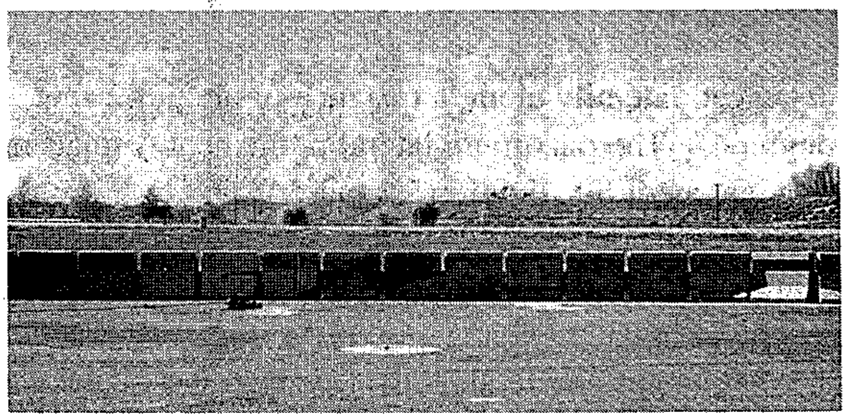
There was longitudinal movement from segment 37 to 84. The maximum longitudinal displacement in the downstream direction was 0.16-feet (0.05 m) at segment 55. The maximum longitudinal displacement in the upstream direction was 0.2-feet (0.06 m) at segment 64.

6.2.6.4 Dummy's Response

During the impact the unrestrained dummy hit the left front door when its head went out the window. The dummy continued to move outward; its forehead hit the top of the barrier. When the dummy came to rest, its upper body was leaning out the window (Figure 55).

There was no physical damage to the dummy.

FIGURE 52. TEST 446 BARRIER DAMAGE



Tire and Wheel Scuffs on Barrier Impacted Segments.

FIGURE 53. TEST 446 BARRIER LATERAL DISPLACEMENT

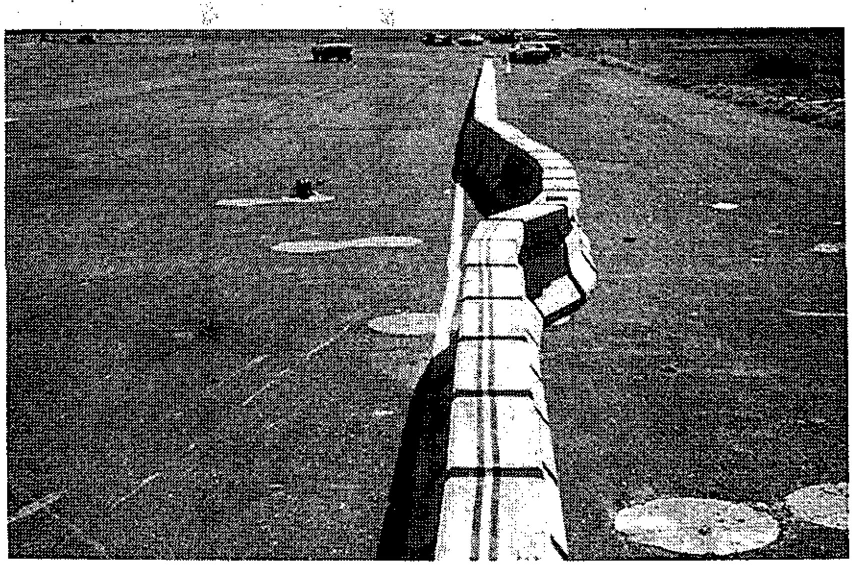


FIGURE 54
TEST 446 BARRIER JOINT LATERAL DEFLECTION DIAGRAM

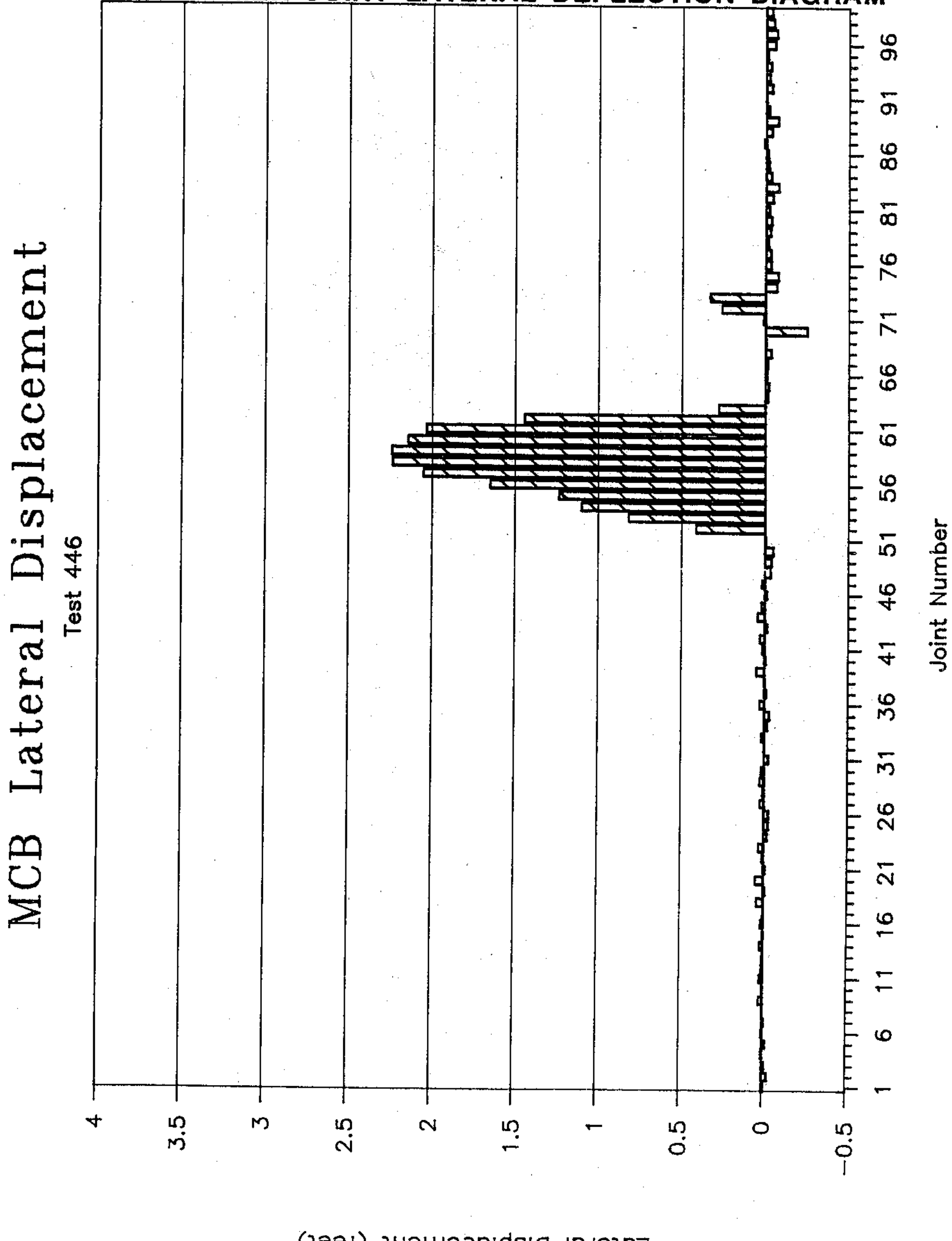


FIGURE 55. TEST 446 DUMMY'S FINAL POSITION

Dummy's Body Leaning out the Window.

6.3 DISCUSSION OF TEST RESULTS

6.3.1 General - Safety Evaluation Guidelines

Three evaluation factors are used to judge the crash test performance of median barriers, as recommended by NCHRP Report 230 (3). These factors are: (1) structural adequacy, (2) occupant risk, and (3) vehicle trajectory.

6.3.2 Structural Adequacy

The structural adequacy was evaluated by comparison of test results with the following criteria from Table 6 of NCHRP Report 230(3):

"A. Test article shall smoothly redirect the vehicle; the vehicle shall not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.

D. Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic."

In tests 443 through 446 the test barrier consisted of 100 segments; there were 40 segments in tests 441 and 442. The additional segments were used for the following reasons:

> In the first two tests, longitudinal movement of the barrier was observed. Additional segments were desired on the upstream end so that the total number of segments involved in longitudinal movement could be monitored.
>
> In the first two tests, the car steered back toward the barrier after redirection. Additional segments were desired on the downstream end so that a second impact could be observed.

In tests 443 through 446 the MCB demonstrated its ability to retain and redirect a vehicle under a variety of impact conditions. Vehicle redirection was very smooth in these tests. There was no tendency for the barrier to pocket or trap the impacting vehicles. In these tests there was no evidence of any structural distress of the barrier segments; there were no visible cracks. All four tests were performed on the same set of barrier segments without need to replace any steel hinge pins, welded hinge plates, or concrete modules (although they were rearranged to present a clean face in the impact area).

The barrier designs used in Tests 441 and 442 were not adequate for meeting the "D" criterion for structural adequacy due to the lack of integrity of the barrier segments. Concrete breakage in the neck section of the segments, due to narrowness of the neck, and insufficient reinforcing steel were the main reasons that the barrier was redesigned by the manufacturer.

The segments in the impact zone for Test 441 had reinforcing steel in the neck section, but the steel did not extend into the overhang of the cap. This allowed a large chunk of the cap to be broken off, and the moment induced in the neck during impact allowed significant cracks to develop in the neck below the overhang.

The segments in the impact zone for Test 442 were cast with steel fiber reinforcing. There was no other reinforcement. The moment induced in the neck during impact was sufficient to break the cap portion of the barrier entirely off. It is unknown if the steel fiber could have limited the size of chunks if the neck had also been conventionally reinforced as in Test 441.

Even though tests 441 and 442 failed criterion "D" above, the vehicles were adequately redirected without penetration, and the overall adequacy of the barrier connection was demonstrated.

In all tests (441 through 446) there was significant lateral displacement of the test barrier. In tests 441 and 442 this was quite large. Tests 443 through 446 showed that lateral displacement can be decreased by restraint of longitudinal movement. The barrier was restrained through two mechanisms. First, segments were added upstream to provide some that would remain stationary. Second, the hinge clearance was reduced, causing more segments to be mobilized for each unit of longitudinal movement.

Table 1 shows that the lateral displacement was reduced by these variations in the test barrier. Tests 442 and 443 had similar impact conditions and lateral displacement was reduced from 4.56-feet (1.39 m) to 3.74-feet (1.14 m). The differences between barriers in tests 442 and 443 were the hinge clearance and locking channel. A comparison of lateral deflection in test 442 to that of a similar barrier, tested by Barrier Systems (6), with the same hinge clearance, but without a locking a channel (for more see Appendix G) shows that the locking channel appears to have no effect on barrier lateral displacement. The deflection of the test 442 barrier at an impact severity of 95.4 ft-kips (129,000 J) is higher than the predicted lateral displacement of the test 443 barrier for the same impact severity using the relations in section 6.4.1. This difference is due to the smaller hinge clearance of the test 443 barrier (3/8-inch = 0.01 m) as compared to the test 442 barrier (1 inch = 0.025 m) and the longer test barrier with stationary segments at the upstream end.

TABLE 1
LATERAL DISPLACEMENT OF BARRIER

Test #	Vehicle Weight lb (kg)	Impact Speed mph	Impact Angle Degrees	Impact Severity ft-kips (kJ)	Max. Permanent Lateral Displacement,D ft (m)
441	4210 (1910)	59.3	15 3/4	36.4 (49.4)	5.76 (1.76)
442	4020 (1823)	61.9	25 1/2	95.4 (129.4)	4.56 (1.39)
443	4370 (1982)	59.3	24	85.0 (115.3)	3.74 (1.14)
444	2000 (907)	57.7	15 1/2	15.9 (21.6)	1.78 (0.54)
445	4300 (1950)	59.4	16	38.4 (52.1)	2.85 (0.87)
446	1895 (857)	58.6	20 1/2	26.7 (36.2)	2.24 (0.68)

The barrier displacement was closely related to impact severity (IS) in tests 443 through 446. The data from these tests were statistically analyzed to obtain an equation for lateral displacement as a function of impact severity (See 6.4).

The entire energy due to the velocity component perpendicular to the barrier (IS) must be absorbed for effective vehicle retention. This is accomplished through work performed on the barrier resulting in lateral deflection and deformation of the vehicle. As a result of the direct dependence of lateral deflection on impact severity, it seems that the permanent displacement of the barrier accounts for the most important part of the kinetic energy component perpendicular to the barrier. This statement is confirmed by the moderate damage to the crash cars typical of all these tests.

In summary, the movable concrete barrier used in tests 443 through 446 was judged structurally adequate.

6.3.3 Occupant Risk

The occupant risk was evaluated by comparison of test results with the following criteria from Table 6 of NCHRP Report 230 (3):

"E. The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.

F. (Applies to 1800 lb/60 mph/15° test only). Impact velocity of hypothetical front seat passenger against vehicle interior, calculated from vehicle accelerations and 24 in. (0.61 m) forward and 12 in. (0.30 m) lateral displacements, shall be less than:

Occupant Impact Velocity-fps	
Longitudinal	Lateral
$40 / F_1$	$30 / F_2$

and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger impact should be less than:

Occupant Ridedown Accelerations-g's	
Longitudinal	Lateral
$20 / F_3$	$20 / F_4$

where F_1, F_2, F_3, and F_4 are appropriate acceptance factors" (Reference 3 recommends in the Commentary that F_1, F_3, and F_4 be 1.33 and F_2 be 1.50).

"G. (Supplementary) Anthropometric dummy responses should be less than those specified by FMVSS 208, i.e., resultant chest acceleration of 60 g, Head Injury Criteria of 1000, and femur force of 2250 lb (10 kN) and by FMVSS 214, i.e., resultant chest acceleration of 60 g, Head Injury Criteria of 1000 and occupant lateral impact velocity of 30 fps (9.1 m/s)."

Table 2 shows roll, pitch and yaw values, occupant impact velocities and maximum 50 ms average accelerations, and ridedown accelerations for tests 443 through 446. Included in the table, for comparison, are the same data from previous tests on concrete safety shape barriers tested by Caltrans.

Note that the magnitude of roll in tests 443 through 446 is generally lower than in other tests of concrete safety shape barriers. In all MCB tests the amount of roll and pitch may be considered light to moderate. None of the test cars, even the front wheel drive 1800-lb car, showed any indication of being close to rollover.

The scuff and rub marks on the face of the barrier indicated that the projecting cap of the MCB restricted the climb of the car.

There was no deformation or intrusion into the passenger compartment.

The longitudinal occupant impact velocity in Test 444 (see Table 2) was less than the NCHRP recommended maximum value and also smaller than in other Caltrans tests on permanent concrete median barriers. Although this was the only test required to meet Section F of the occupant risk requirements of NCHRP Report 230 (3), the criterion was also met in Tests 443, 445, and 446.

The low values of longitudinal impact velocity illustrate the smooth movement of the cars along the barrier and the lack of snagging which helps to lower the risk to passengers. The lateral occupant impact velocity was calculated for two tests (443 and 445). These lateral occupant impact velocities are lower than the longitudinal ones. Consequently, the assumption that lateral velocities for the other tests are lower than the longitudinal ones may be reasonable. Test 444 (2000 lb/60 mph/15°), which emphasized on evaluation of the risk to occupants during a 15° angle of impact, has a longitudinal impact velocity significantly lower than the suggested limit value. Even test 443 (4500 lb/60 mph/25°), which was intended to be a most severe impact expected with a passenger vehicle, had a reasonably low value for longitudinal occupant impact velocity.

The second part of Criterion F in NCHRP Report No. 230 calls for a highest 10 ms. average value of longitudinal and lateral vehicle acceleration of 15 g's

TABLE 2
TEST RESULTS

Test # Concrete Barrier Type	443 MCB	444 MCB	445 MCB	446 MCB	451 (7) New Jersey	431 (8) New Jersey	262 (9) Type 50	263 (9) Type 50	162 (10) New Jersey	161B (10) New Jersey
Car Weight, lb (kg)	4370 (1982)	2000 (907)	4300 (1950)	1890 (857)	3575 (1622)	1860 (844)	4960 (2250)	4960 (2250)	4540 (2060)	4540 (2060)
Impact Angle,degree	24	15 1/2	16	20 1/2	45	52	25	25	25	7
Speed, mph (m/s)	59.3 (26.5)	57.7 (25.8)	59.4 (26.6)	58.6 (26.2)	40.3 (18.0)	27.4 (12.2)	59.0 (26.4)	66.0 (29.5)	63.0 (28.2)	65.0 (29.1)
Roll, degree	-10 1/4	-14 1/2	6 1/4	-15	7 1/2	71	>90	>90	25	14
Pitch, degree	NA	10 1/4	5 3/8	12 1/2	NA	-2	NA	NA	NA	NA
Yaw, degree	NA	NA	NA	NA	NA	-12	NA	NA	NA	NA
Maximum rise, in.	4.4	16.7	19.3	29.6	NA	NA	34	32	NA	NA
Max. 50 ms Average Acceleration, g										
Longitudinal[1]	-8.3	-4.6	-3.3	-7.6	-11.2	-12.4	7.0	NA	NA	NA
Lateral[2]	-7.7	-6.7	-5.9	-11.3	-8.7	-5.5	11.6	NA	NA	NA
Occupant Impact Velocity, fps (m/s)										
Longitudinal[3]	27.0 (8.2)	15.1 (4.6)	14.3 (4.4)	16.9 (5.2)	28.6 (8.7)	32.9 (10.0)	NA NA	NA NA	NA NA	NA NA
Lateral[4] (from digital recorder)	18.0 (5.5)	NA	14.0 (4.3)	NA	NA	NA	NA	NA	NA	NA
Ride down Accelerations, g[5]										
Longitudinal	-5.6	≤15	-3.9	≤15	NA	-15	NA	NA	NA	NA
Lateral	7.6	≤15	10.6	≤15	NA	-10	NA	NA	NA	NA
HIC[6]	121	30	45	86	242	317	NA	NA	NA	NA

1. TRC 191 recommended maximum value: -5g (acceptable value -10g)
2. TRC 191 recommended maximum value: -3g (acceptable value -5g)
3. NCHRP Report 230 recommended value: 30 fps (9.1 m/s)
4. NCHRP Report 230 recommended maximum value: 20 fps (6.1 m/s)
5. NCHRP Report 230 recommended maximum value: 15 g's
6. HIC - Head Injury Criterion - maximum value = 1000

after the theoretical occupant/compartment impact occurs. In all tests, 443 through 446, these values were much less than 15 g's for a 10 ms duration as determined by inspection of the acceleration vs time plot (See Table 2).

The former method of evaluating occupant risk, then called impact severity, was to calculate the maximum 50 ms average lateral and longitudinal vehicle accelerations.

Actual values for movable concrete barrier impact tests show that maximum 50 ms average accelerations in the lateral direction exceeded the former acceptable values in almost all tests.The highest value of lateral acceleration was the result of an 1890 lb (857 kg) car impacting the barrier at a 20° angle and with a speed of 59 mph (26.4 m/s) (test 446).

Other researchers (11) have found that the lateral acceleration cannot be reduced below -5 g's when small cars impact a fairly rigid barrier at angles of 15 degrees and speeds of 60 mph (26.8 m/s). The 50 ms average acceleration in the longitudinal direction did not exceed the limit, that is, the impact was very smooth.

One of the supplementary requirements in criterion G, the head injury criterion (HIC), was calculated for all tests. These values were much less than the upper limit of 1000, which marks the threshold of serious injury or death.

It should be noted that none of the above means of evaluating the occupant risk are exact methods of predicting injury levels during impacts. NCHRP Report 230 states that "Whereas the highway engineer is ultimately concerned with safety of the vehicle occupants, the occupant risk criteria should be considered as the guidelines for generally acceptable dynamic performance. These criteria are not valid, however, for use in predicting occupant injury in real or hypothetical accidents". The explanation is given that "relationship between vehicle dynamics and probability of occupant injury and degree of injury sustained is tenuous, because it involves such important but widely varying factors as occupant physiology, size, seating position, restraint, and vehicle interior geometry and padding". However, the low occupant/compartment impact velocity and ridedown acceleration values indicate safe highway appurtenances.

In summary, the MCB used in tests 443 through 446 met the occupant risk evaluation factors.

6.3.4 Vehicle Trajectory

The vehicle trajectory was evaluated by comparison of test results with the following criteria from Table 6 of NCHRP Report 230 (3):

"H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.

I. In tests where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mph and the exit angle from the test article should be less than 60% of test impact angle, both measured at time of vehicle loss of contact with test device."

The same report stresses that "trajectory evaluation for redirectional type of tests is focused on the vehicle at the time it loses contact with the test article, and the subsequent part of the trajectory is not evaluated."

The exit angles for all tests exceeded the recommended upper limit of 60% of the impact angle (Table 3).

The vehicle speed change was less than the 15-mph (6.7 m/s) limit for tests 444 through 446. These low changes in vehicle speed correspond to the relatively low values of longitudinal vehicle acceleration.

The exit velocity (27.0 mph = 12.1 m/s) in test 443 represented a speed change of 32.3 mph (14.4 m/s) which was greater than the 15-mph (6.7 m/s) limit. This change in speed corresponds to the high longitudinal vehicle acceleration. The exit speeds are not available for tests 441 and 442.

Regardless of speed change and exit angles, the barrier demonstrated its ability to retain a vehicle under very severe impact conditions. There was no tendency to pocket or snag the car.

TABLE 3

Test number	Impact Angle deg	60% of Impact Angle, deg	Exit Angle deg	Impact Speed, V_I mph (m/s)	Exit Speed, V_E mph (m/s)	Speed Change V_I-V_E mph (m/s)
441	15 3/4	9 3/4	21 1/4	59.3 (26.5)	NA	NA
442	25 1/2	15 1/4	NA	61.9 (27.7)	NA	NA
443	24	14 1/2	14 3/4	59.3 (26.5)	27.0 (12.1)	32.3 (14.4)
444	15 1/2	9 1/4	10 1/4	57.7 (25.8)	45.8 (20.5)	11.9 (5.3)
445	16	9 1/2	16 1/2	59.4 (26.6)	48.0 (21.5)	11.4 (5.1)
446	20 1/2	12 1/4	19 1/2	58.6 (26.2)	47.6 (21.3)	11.0 (4.9)

Following the barrier impact, the vehicles rebounded from the barrier in a disabled condition and traveled 100 to 220-feet (30 to 67 m) before coming to a stop.

The car postimpact trajectories followed two different patterns. In tests 441 through 443, the cars were redirected toward the line of the barrier. Their final positions were across the line of the barrier. In tests 442 and 443, the cars made secondary impact with the barrier (Figures 22 and 30). If the barrier had extended further downstream, the vehicle would have impacted it a second time in test 441. In tests 444 through 446, the cars were redirected outward from the test barrier and stopped 40 to 60-feet (12 to 18 m) from the barrier face.

The difference in vehicle trajectory may be attributed to variations in the timing of brake application and vehicle characteristics, such as weight distribution, suspension system, tires, vehicle stability after impact, and vehicle damage. For all tests, the postimpact trajectory was difficult to relate to exit angles and speeds. But, NCHRP Report No. 230 (3) points out, "the after collision trajectory may be one of the least repeatable performance factors" and "there is no assurance that existing hardware or certain classes of appurtenances will perform within" NCHRP Report 230 limits for exit angle and speed.

In summary the MCB used in tests 443 through 446 did not meet the vehicle trajectory requirements of NCHRP Report 230 (3).

6.4 Discussion of Other Evaluation Factors

6.4.1 Predicting Maximum Lateral Displacement

When considering a location for applying this barrier, a predictive model for projecting the maximum expected lateral displacement will be needed. Such a model could be used to help assess the risk of installing a movable barrier in a particular location or to evaluate the severity of an accident that has happened. Bryden, et al, used a similar method to assess the risk of barrier deflection into opposing traffic on Tappan Zee Bridge (12).

Data from tests 443 through 446 and also from tests performed by Barrier Systems, Inc. were analyzed to empirically derive an equation relating impact severity to the maximum lateral displacement of the barrier.

Analysis was by least square curve fitting using a computer program (13). Maximum displacement (D) and impact severity (IS) were each used as the dependent variable. Appendix E contains a detailed discussion of the analyses.

Two equations were found to fit the experimental data of lateral displacement as a function of impact severity. These equations are shown in Table 4 and represented in Figure 56.

FIGURE 56.
MCB MAXIMUM DISPLACEMENT MODELS

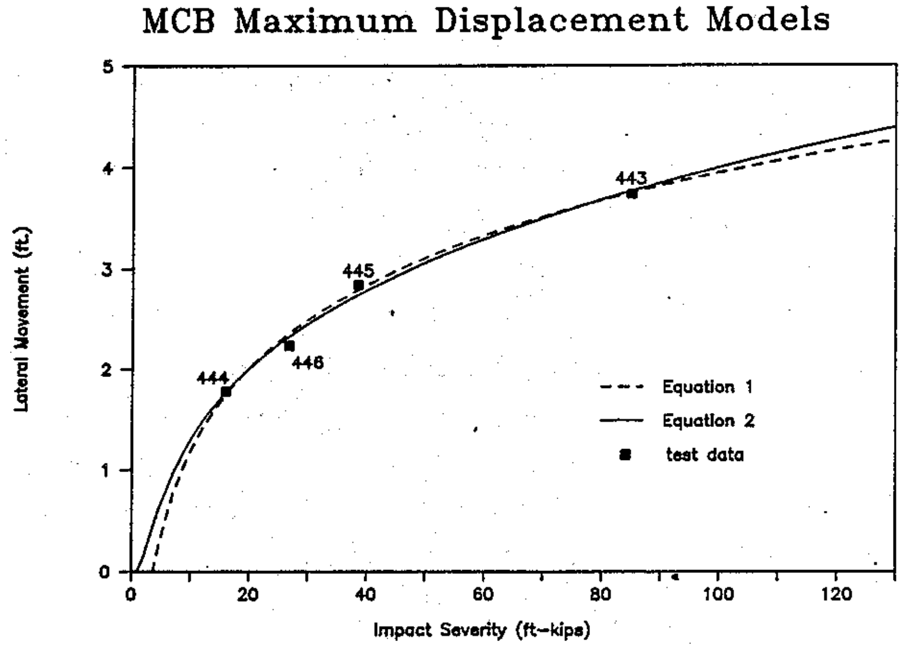


TABLE 4

Eq. #	Equation	Coefficients A	B	C	Applicable IS Range ft-kips (kJ)
1	D = A + B ln(IS)	-1.62 (-0.592)	1.21 (0.365)	- -	15.to 130 (20 to 175)
2	D = A + B $^{1/IS}$•IS^{C}	0.961 (0.266)	0.0125 (0.00263)	0.319 (0.319)	1.to.130 (1 to 175)

The correlation coefficient is 0.9934 for equation 1 and 0.9856 for equation 2. Note that the first equation is valid for values of IS from 15 to 130 ft-kips, (20 to 175 kJ) whereas the second equation covers values of IS from 1 to 130 ft-kips (1 to 175 kJ).

For very small values (up to 3.8 ft-kips, 5.2kJ) no deflection is predicted by equation 1. Although the second equation approaches a zero displacement as IS approaches zero, it can be considered to equal zero when IS is less than one.

For small impacts, up to 15 ft kips (20 kJ), the researchers believe that equation 1 understates the displacement that might be expected. Within this impact severity range, equation 2 probably gives a better value of lateral displacement. The reason that the lateral displacement is probably larger than that predicted by equation 1 lies in the action within the hinge during impact. In high IS value impacts like those used to derive equation 1, many of the barrier segments enter into movement. For each barrier segment that moves, the entire 3/8-inch (0.01 m) longitudinal clearance in the hinge is taken up to allow lateral movement. During low energy impacts fewer segments are brought into the movement zone, down to the limiting case where only two segments move. In an impact when only two or three segments move, all of the longitudinal hinge clearance may not be used; thus, allowing movement with very low energy input.

Within the range of 15 to 130 ft-kips (20 to 175 kJ) the two equations give the same answer within the range of accuracy that can be expected from such an estimator. Caution must be exercised when using these equations to extrapolate beyond 100 ft-kips (135 kJ) because that is beyond the value of any data used for deriving the equations.

At some unknown value of impact severity, some structural elements of the barrier may fail, thus, invalidating any attempt at deflection prediction.

There may be some cases where, given the barrier movement, the impact severity is desired. For values within the range of the logarithmic equation (equation 1), it can be solved for IS, the form will be $IS = A \bullet \exp^{(BD)}$(equation 3).

Equation 2 cannot be solved for IS. For values outside the applicable range, a different equation must be used.

The equations for deriving impact severity as a function of lateral displacement, their coefficient and application ranges are given in Table 5.

TABLE 5

Eq, Number	Equation	Coefficients A	B	C	Applicable Lateral deflection (D) range, ft (m)
3	$IS = A\exp(BD)$	3.81 (5.17)	0.828 (2.72)	-	1.6 to 4.2 (0.5 to 1.2)
4	$IS = AB^{D} D^{C}$	3.91 (9.27)	1.92 (8.50)	0.470 (0.470)	0.1 to 4. (0.3 to 1.2)
5	$IS = A\left(\frac{D}{B}\right)^{C}\exp\left(\frac{D}{B}\right)$	4.78 (6.49)	1.53 (0.467)	0.470 (0.470)	0.1 to 4. (0.1 to 1.2)

Equations 4 and 5 are equivalent. The difference between them is less than 1% (from 0.1% at IS = 1 to 0.7% at IS = 130). Both equations fit the data equally well.

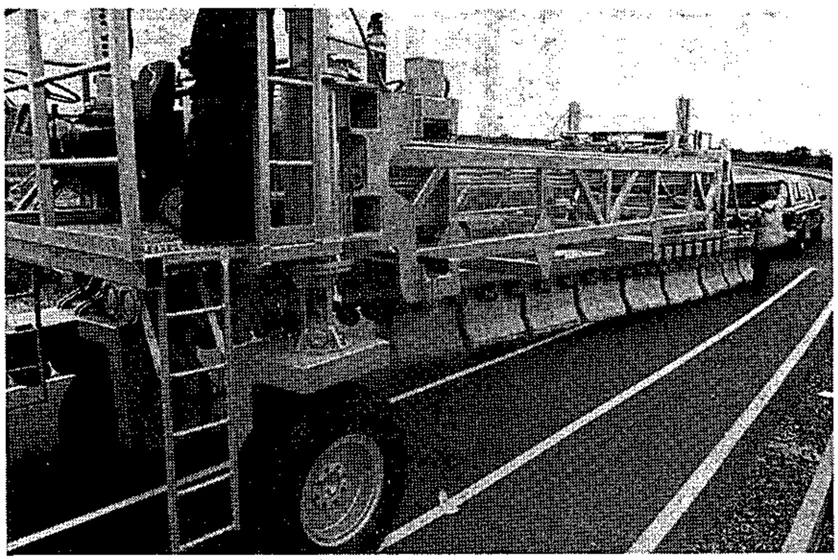
6.4.2. Transfer Vehicle Operation

6.4.2.1. The Transfer Vehicle

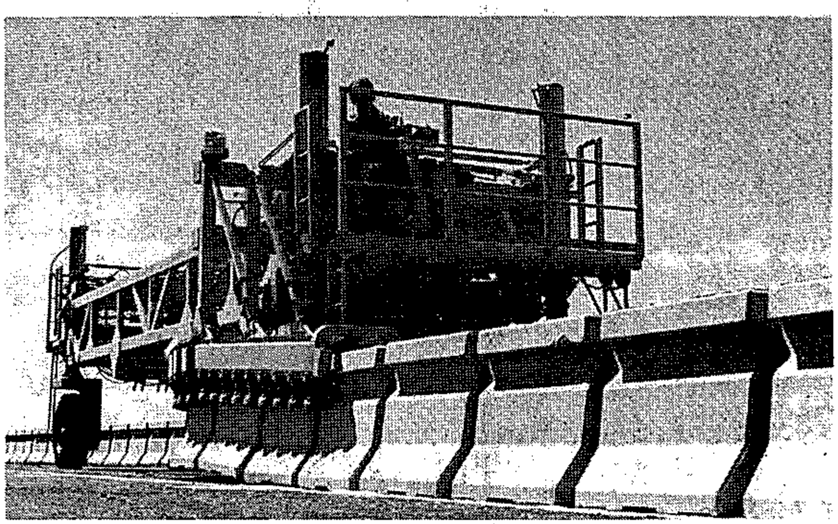
The transfer vehicle was manufactured for Barrier Systems, Inc. per their specifications. It is 46-feet (14 m) long, 8.2-feet (2.5 m) wide and weighs 31,700 lb (14,380 kg) (Figure 57). It is self-powered; a 153-HP (113 kW) diesel engine powers a hydraulic drive and steering. Each wheel of the machine can be independently raised and lowered. Up to 15 segments of the barrier (almost 50 feet or 15 m) can be transported as a unit at one time. A barrier can be transferred onto or off of a curb up to 12-inches (0.3 m) high. The lateral move of the barrier can be varied from 6 to 16 feet (1.8 to 4.9 m). The transfer vehicle operates in either direction and is operationally symmetrical. Each end of the vehicle is independently steered with its own steering wheel. Movement can be controlled from either end.

A study to predict the asphalt concrete (AC) deformation produced by a transfer vehicle was performed (see Appendix I). State-of-the-art models used in this

FIGURE 57. TRANSFER VEHICLE



Over-all View



Close-up View of Lifting System

Close-up View of Hydraulic System

study predict practically unlimited service life for an AC wearing course on a PCC bridge deck using the transfer vehicle. Nevertheless, the load distribution in the contact area and viscoelastic behavior of the AC may not be accurately represented by the simplifying assumptions of the model. More importantly, frequent pivoting for barrier alignment will greatly reduce predicted service life of AC layers. A strong recommendation was made to closely monitor pavement surface condition where the transfer vehicle is used.

6.4.2.2. Demonstrations of Transfer Vehicle

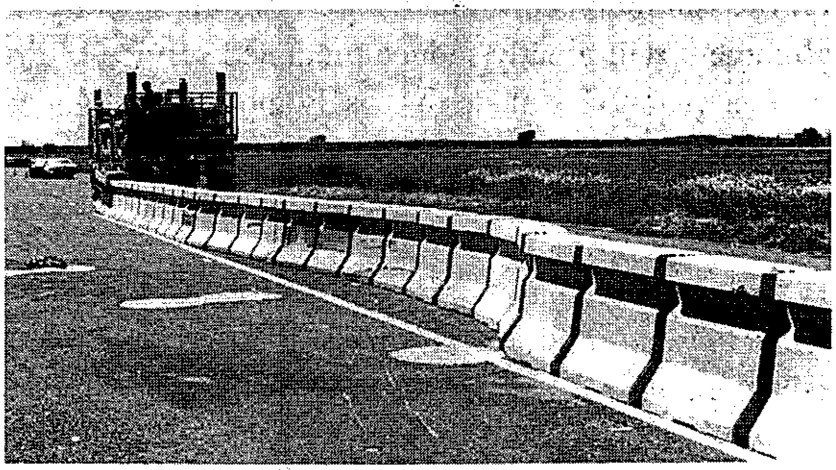
A prototype transfer vehicle was used for the 4 demonstrations involved in this project. They were: 1) straightening a deflected barrier after the last crash test, 2) transporting and assembling lengths of barrier 10-segments long, 3) transferring barrier on a 1400-foot (427 m) radius with a 12% cross slope, and 4) transferring barrier on a 4 to 5% longitudinal grade.

The first demonstration showed the ability of the transfer vehicle to realign a deflected barrier. The barrier was deflected by test 446 a maximum of 2.24 feet (0.68 m). The barrier was back to a straight alignment in its original position after two passes (Figure 58). It appeared that with more experienced operators the alignment could probably have been made straight with only one pass. Two additional passes were made over the barrier to demonstrate simple transfer operation. All the functions of the transfer vehicle, lifting off, lateral transport and deposit of the modules, were smooth and continuous.

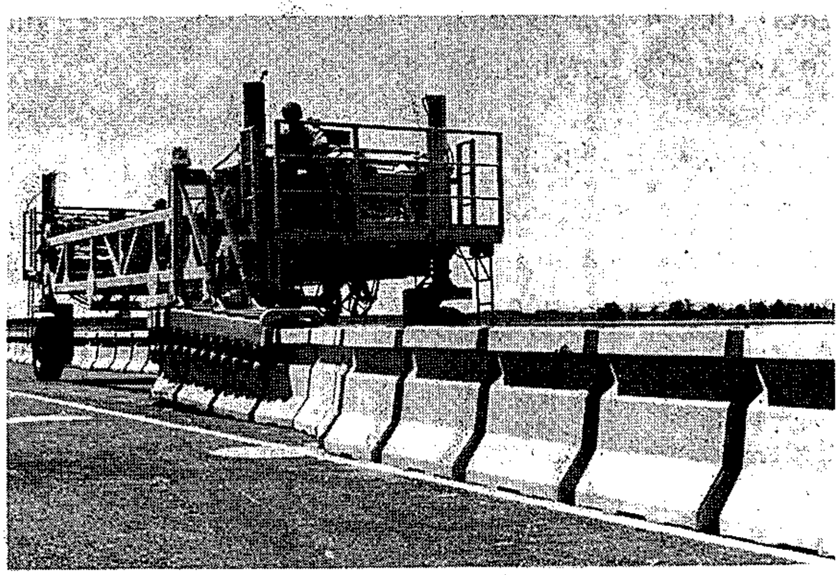
In simple transfer operations, the vehicle moved at about 6-miles per hour (2.7 m/s). Realignment was accomplished without the need for workers to manually adjust the barrier.

The second demonstration showed how lengths of barrier can be transported and reattached to a standing barrier. Such an operation might be performed in moving the lane closure zone of a progressing construction site. This demonstration consisted of picking up a length of barrier (10 segments), carrying it to the location of the third demonstration and reassembling it.

FIGURE 58. REALIGNMENT OF DEFLECTED BARRIER



2.24-feet (0.68 m) Deflection of Barrier



First Pass for Realignment

Second and Final Realignment Pass

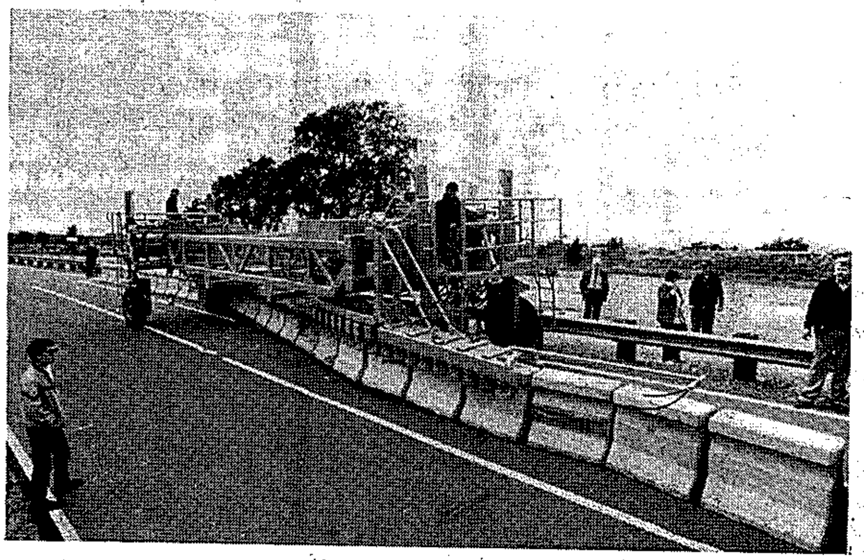
The transport distance was about one-half mile (800 m), which included about 400 feet (120 m) of rough dirt road. Travel speed on the paved road was about10 miles per hour (4.5 m/s). Travel on the dirt road was much slower (1 to 4 mph or 0.5 to 1.8 m/s); the vehicle was designed for use on paved roads.

Reassembly consisted of aligning the placed barrier with that carried by the vehicle and inserting the hinge pin. To align the 2 segments of barrier to be joined, the section on the ground was loaded partly into the conveyor until it came in contact with the barrier being carried. There was some difficulty inserting the pin when the joint to be connected was pushed too far into the vehicle, to a place that hampered pin insertion. Even with that problem, set-up of the barrier was much faster than if it had been installed one segment at a time.

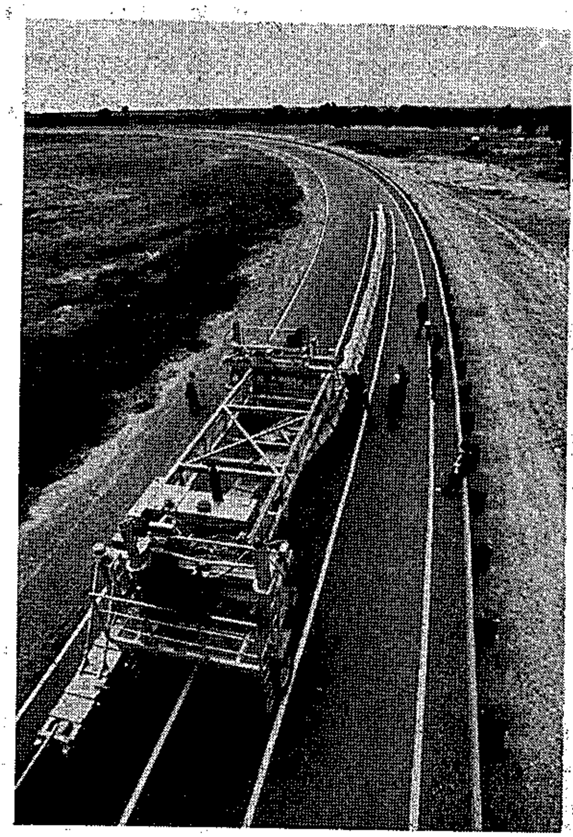
The third demonstration consisted of transferring a barrier plus and minus 6 feet (1.8 m) from its original position on a 1400-foot (427 m) radius curve (Figure 59). The barrier was laid out on a 1000-foot (305 m) radius roadway with a 12% cross slope, so the existing pavement stripes could not be used. Two reference lines were laid out, three feet from each of the desired barrier locations, for use by the vehicle operators to place the barrier on each transfer run. A total of 70 segments were used, comprising a barrier 230-feet (70 m) long. Two 4-movement cycles were performed. In one cycle, the barrier was first moved outward to a 1406-foot (429 m) radius, then twice transferred six feet (1.8 m) inward to a 1394-foot (425 m) radius, then transferred outward to the original 1400-foot (429 m) radius. When first transferred to the smallest radius there was a length of about 50 feet (15 m) that was kinked at each segment. When the barrier was moved to the larger radii and back, the 1394-foot radius was smooth and free of kinks. Measurements of barrier elongation and shortening when the radius is changed fell within the expected range, based on theoretical calculations.

The last demonstration, transferring barrier on a 5% longitudinal grade, was done in Lodi at the Barrier Systems Inc. test site (Figure 60). The barrier consisted of 76 segments or 250 ft (76 m). The whole barrier was transferred laterally back and forth six feet (1.8 m) each time from the middle, initial position. The transfer vehicle speed was about 5 miles per hour (2.2 m/s) for both uphill and downhill movements of the transfer vehicle. The barrier segments

FIGURE 59
BARRIER TRANSFER ON A 1400-FOOT RADIUS CURVE

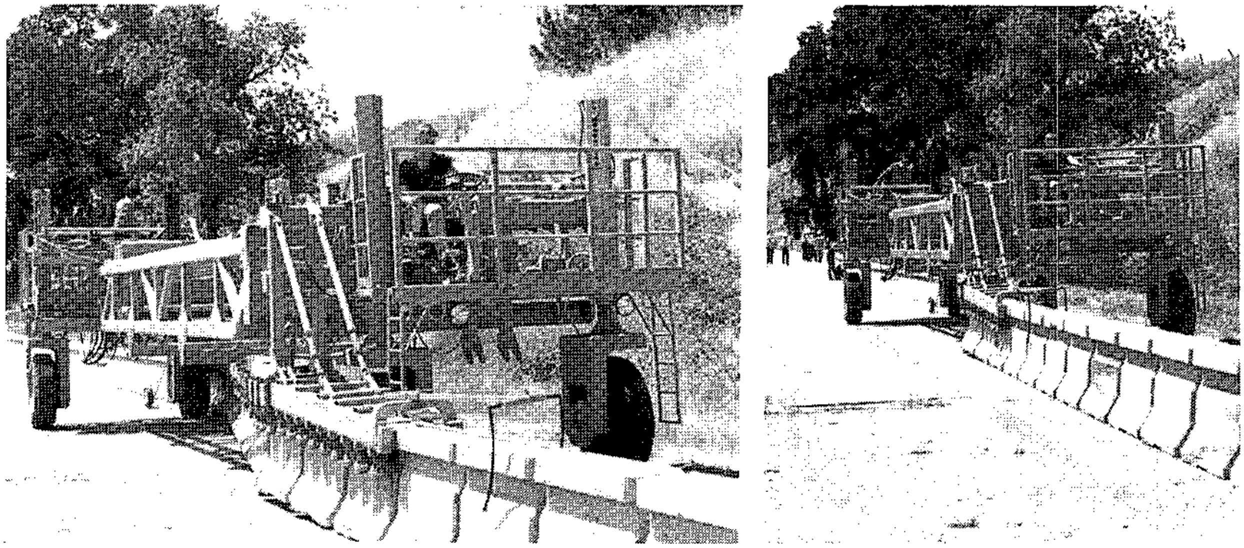


First movement in transfer cycle. Outward movement of the barrier toward 1406-foot radius.



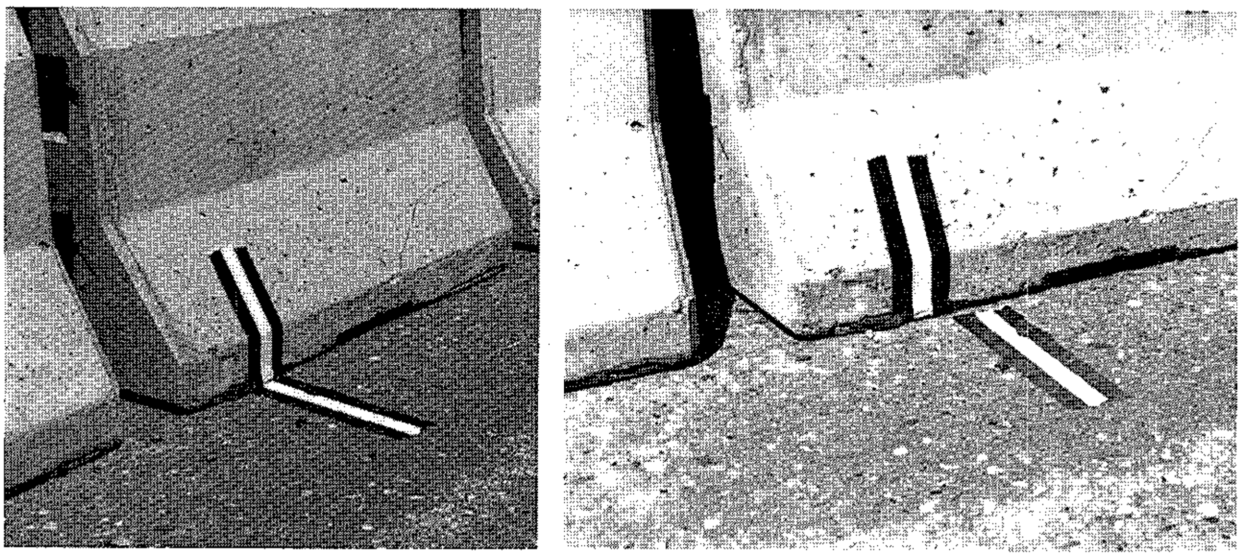
Last movement in transfer cycle - outward movement toward 1400-foot radius. Notice barrier kinks left by third movement during first transfer cycle.

FIGURE 60
LATERAL TRANSFER ON 5% LONGITUDINAL GRADE



Uphill lateral movements of the transfer vehicle.

FIGURE 61. MEASUREMENT OF JOINT DISPLACEMENT DURING TRANSFER ON 5% LONGITUDINAL GRADE



Before Transfer After Transfer

were freestanding in the first eight transfers and tethered in the second set of eight transfers.

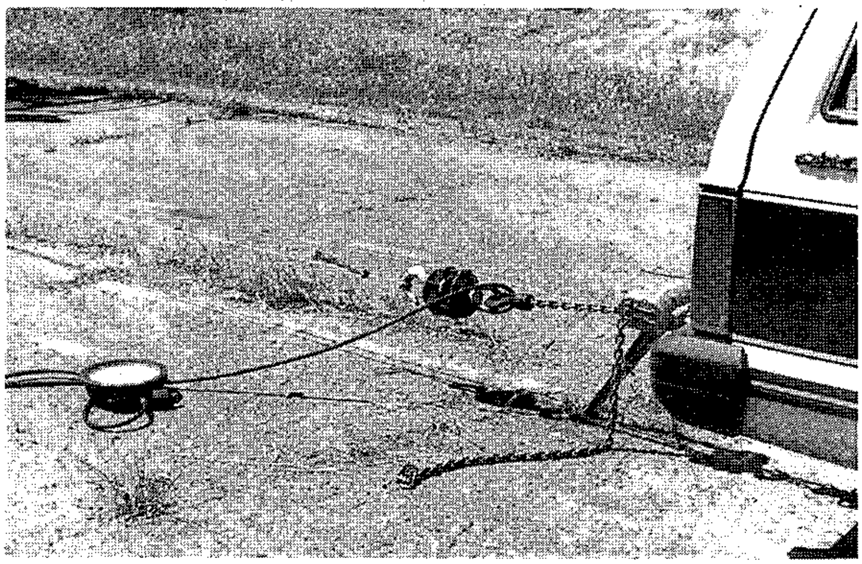
Measurements of the joint displacements were taken across a set of 4 joints located about 50 feet (15 m) from each barrier end (Figure 61). The measurements were taken after each lateral transfer. It was observed that the net change in length was near zero after each complete transfer cycle. Stretching of the barrier apparently occurred during movement of the transfer vehicle uphill, and contraction during downhill transfers. However, the number of transfers was too small to discern a definite pattern.

The lateral transfers resulted in a gradual longitudinal movement of the barrier system downhill. Measurements of longitudinal movement were taken at the downhill end of the barrier. Total longitudinal movement measured was 4-3/4 inches (0.12 m) after 8 lateral transfers. Since the length of the barrier did not seem to change, as evidenced by the measurements above, the whole barrier must have moved longitudinally downhill.

To counteract this tendency, the upstream end of the barrier was tethered with a cable (Figure 62). The cable was tensioned to 1000-lb force (4448 N) at the beginning of each downhill run. The same measurements as for the freestanding barrier were performed. The measurements indicated an apparent stretching of the barrier after each transfer cycle. The stretch was about .01 inch (0.0025 m) per joint. A total longitudinal movement of 1-1/2 to 1-7/8 inches (0.04 to 0.05 m) occurred after 4 lateral transfers. Since the upstream end of the barrier was tethered, the downhill creep may be explained by the stretch in the barrier noted above. Although creep seemed to be restricted by pulling at the upstream end, it was not eliminated. A definite pattern or determination can not be drawn from these data since the number of repetitions was limited.

Longitudinal creep has been reported in a similar barrier system installed in Paris, France (14). The total longitudinal movement of the 1.5-mile (2.5 km) long French barrier on a downhill grade of 1.5 to 2.0% was 3.3 to 6.6 feet (1 to 2 meters) during the initial months of operation. The French solution to retard longitudinal creep was manual jacking of the uphill end of the barrier system before starting each daily barrier transfer in the downhill direction, similar to what was done in this demonstration (see Appendix G). Longitudinal creep has been noticed for 2 construction moveable concrete barriers now in operation in Texas and North Carolina (see Appendix H). The creep was reported as "noticeable" for the North Carolina system installed on a 3% grade. No creep was reported for barriers installed on flat surfaces in North Carolina, Oklahoma, and Pennsylvania.

FIGURE 62



Tethering the upstream end of the barrier

6.4.2.3. Demonstrations of Manual Movement.

Included in the schedule for this project were two demonstrations of tasks that were to be done by hand methods. These were 1) realigning the barrier after an impact, 2) removing and replacing a single segment from a line. Neither of these demonstrations were explicitly performed. Originally it was thought that the transfer vehicle would not be capable of straightening a deflected barrier, hence, the hand method would be required. It has been shown that a transfer vehicle can do this task, so manual demonstration seemed unnecessary. However, while installing the barriers for crash testing there was quite a lot of manual adjustment of the barrier, thus, essentially manual movement was demonstrated but not formally. The required tool is a six-foot (2 m) long pry bar.

Before the end of this project, Barrier Systems Inc. demonstrated, for others, the ability of one man to open a nine-foot (2.7 m) wide vehicular access opening (15). This operation took 3 minutes. This showed that, with the addition of a light crane, removal and replacement of a single segment would be possible and rapid.

In summary, the transfer vehicle can straighten deflected barrier up to 2.24 feet (0.68 m) in one pass. Transporting, assembling, and transferring an MCB on a flat roadway, a 1400-foot (427 m) radius curve with 12% cross slope, and a 5% longitudinal grade were successfully performed by the transfer vehicle.

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The test vehicles were modified as follows for the crash tests:

* The gas tanks on the test vehicles were disconnected from the fuel supply line and drained. Shortly before the test, dry ice was placed in the tanks of the 1800-lb (816 kg) cars as a safety precaution to drive out the gas fumes. A one-gallon (3.78 l) safety gas tank was installed in the trunk compartment and connected to the fuel supply line. On 4500-lb (2041 kg) cars, the gas tank was filled with water prior to the test.

* Six 12-volt wet cell motorcycle storage batteries were mounted in the vehicle. Two supplied power to a high-speed camera and lamps located inside the vehicle. Another pair of batteries operated the solenoid-valve braking system and other test equipment in the vehicle. The third pair of batteries powered the PACDAS data acquisition system.

* The gas pedal was linked to a small cylinder with a piston which opened the throttle. The piston was started by a hand thrown switch on the rear fender of the test vehicle. The piston was connected to the same CO_2 tube used for the brake system, but a separate regulator controlled the pressure.

* A speed control device connected between the negative side of the coil and the vehicle battery regulated the speed of the test vehicle based on speedometer cable output. This device was calibrated prior to the test by conducting a series of trial runs through a speed trap composed of two tape switches set a known distance apart and connected to a digital timer.

* A cable guidance system directed the vehicle into the barrier. The guidance cable, anchored at each end of the vehicle path to a threaded coupler embedded in a concrete footing, passed through a guide bracket bolted to the spindle of the front wheel of the vehicle.

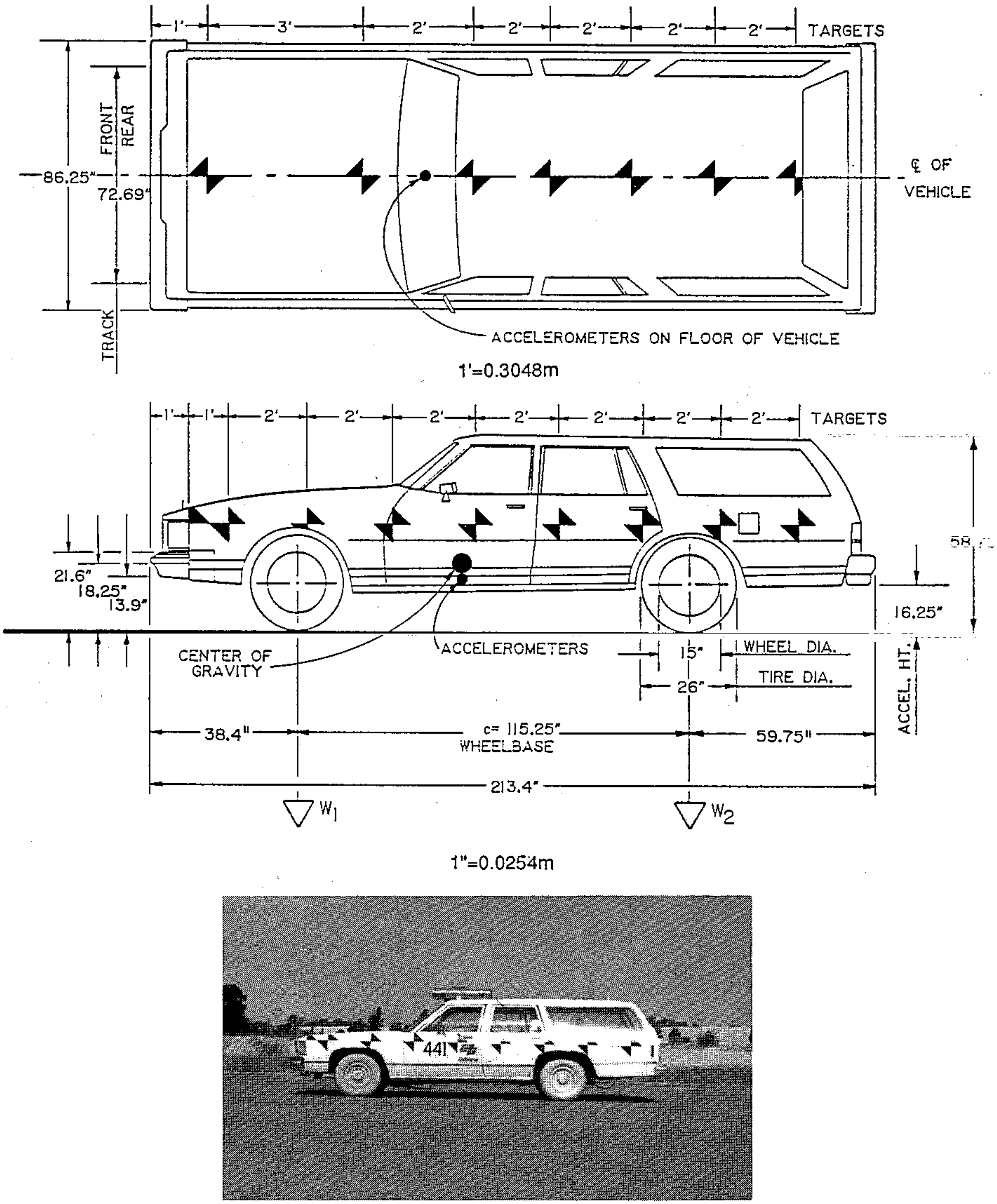
  A steel knockoff bracket, anchoring the end of the cable closest to the barrier to a concrete footing, projected high enough to knock off the guide bracket, thereby releasing the vehicle from the guidance cable before impact.

* A microswitch was mounted below the front bumper and connected to the ignition system. A trip plate on the ground near impact triggered the switch when the car passed over it, thus opening the ignition circuit and cutting the vehicle engine before impact. This switch also released the sliding weight (mounted on top of the car in tests where it was used) from an electromagnet so the weight was free to travel, slightly before the instant of impact.

* A solenoid-valve actuated CO_2 system controlled remote braking after impact or emergency braking any other time. Part of this system was a cylinder with a piston which was attached to the brake pedal. The pressure operating the piston was set during trial runs to stop the test vehicle without locking the wheels. When activated, the brakes were applied in less than 100 milliseconds.

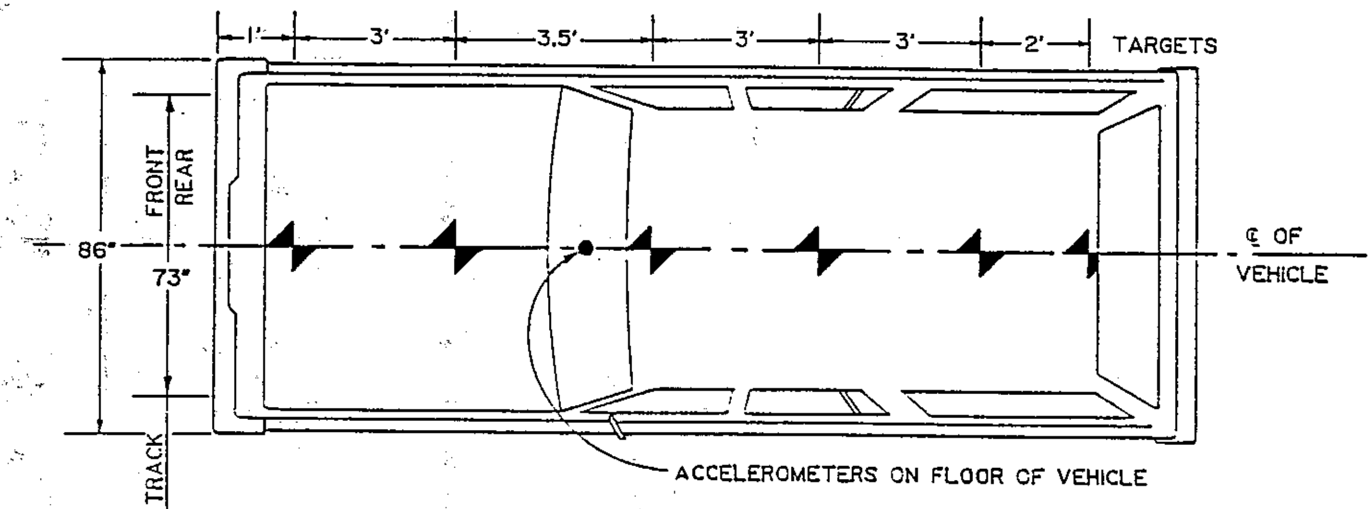
* The remote brakes were controlled at the console trailer. A cable ran from the console trailer to the electronic instrumentation trailer. From there, the remote brake signal was carried on one channel of the tether line which was connected to the test vehicle. Any loss of continuity in these cables activated the brakes and cut off the ignition automatically. Also, when the brakes were applied by remote control from the console trailer, the ignition was automatically cut off.

Figures A1 through A6 on the following pages show the vehicle dimensions. Dimensions were measured.

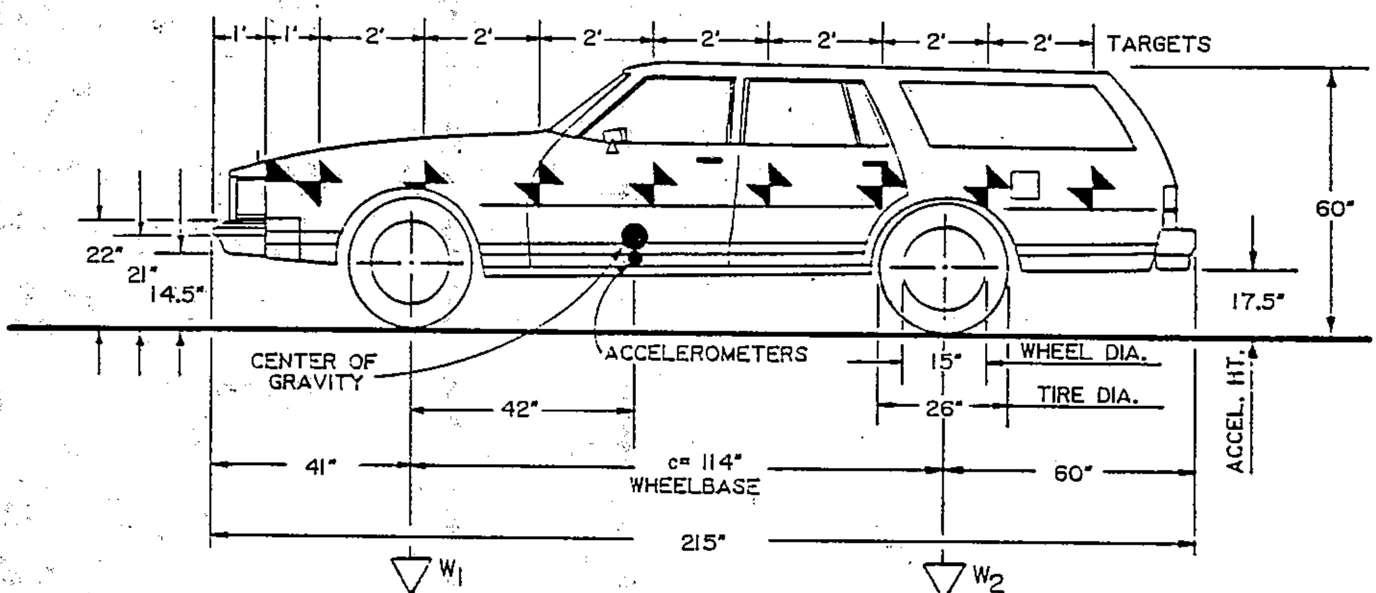


CAR DIMENSIONS

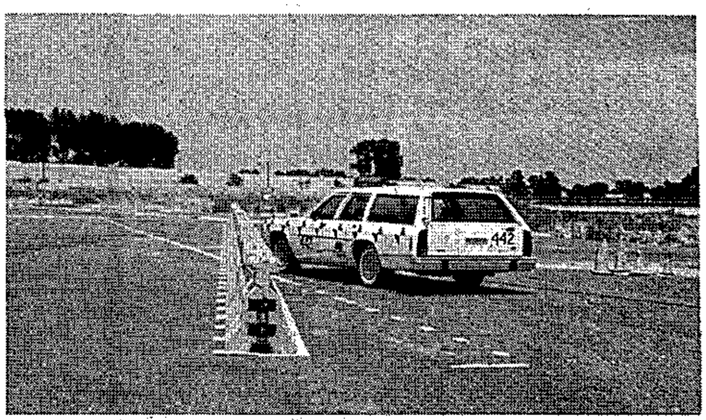
FIGURE A1



1'=0.3048m

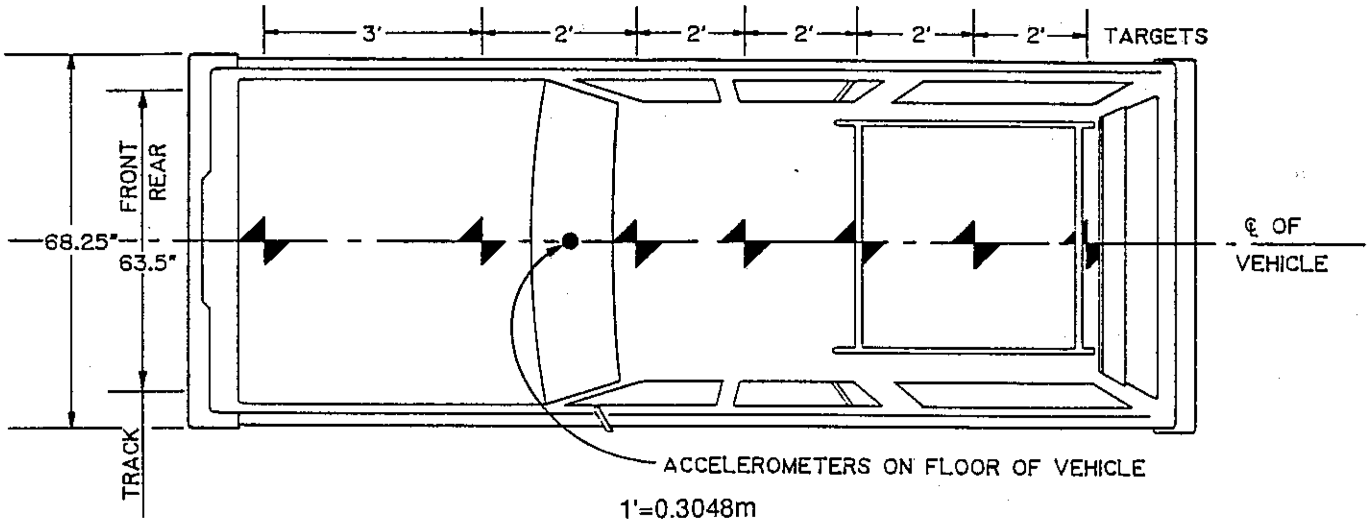


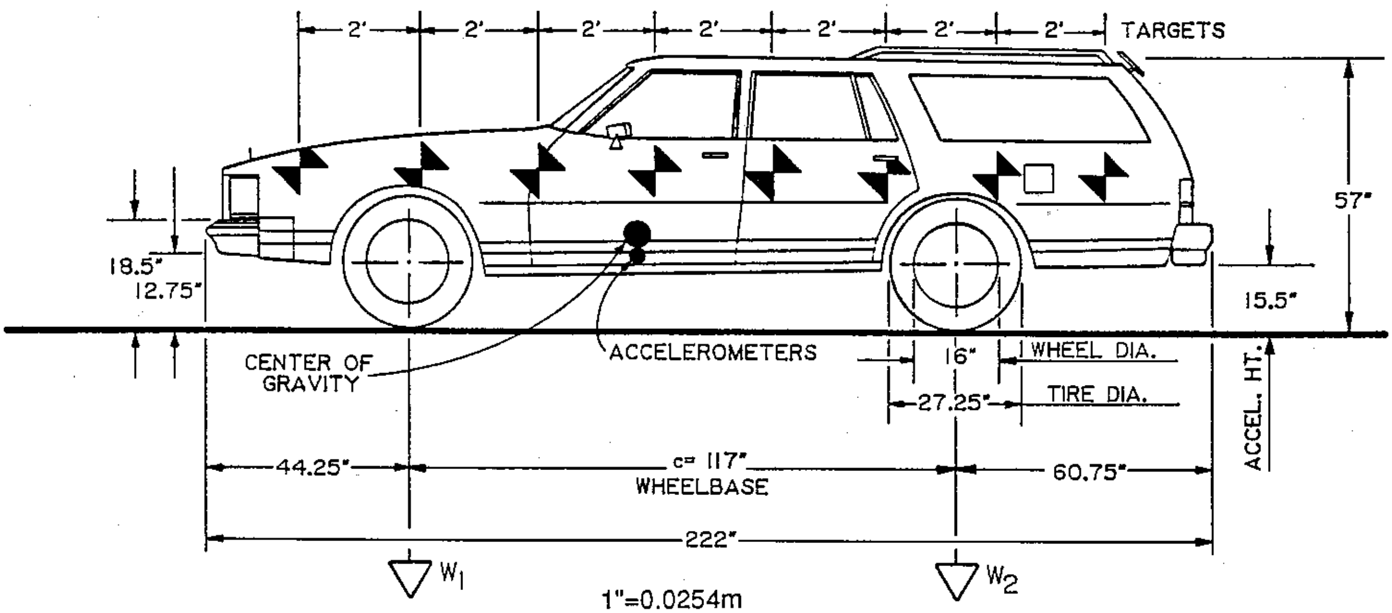
1"=0.0254m



CAR DIMENSIONS

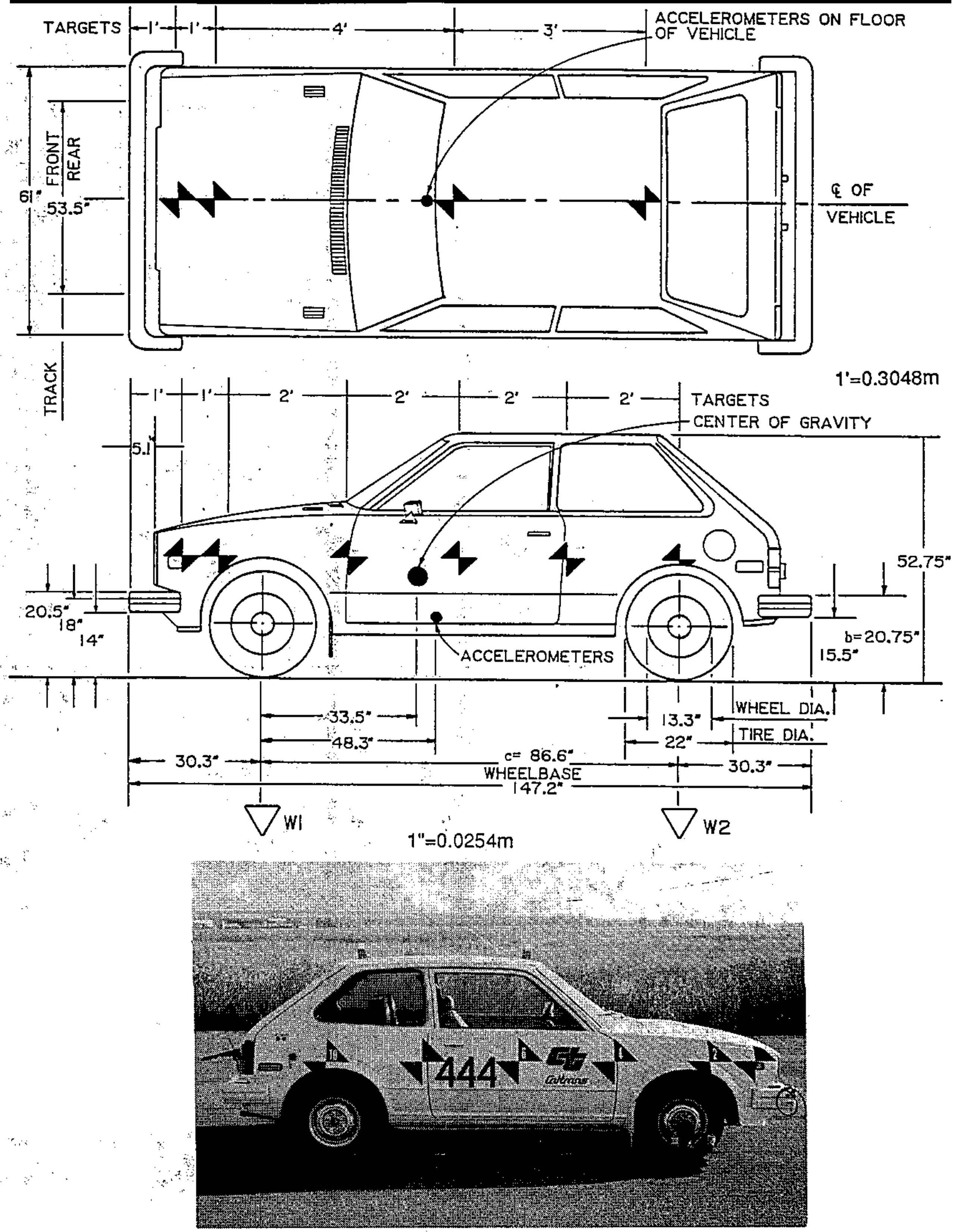
FIGURE A2





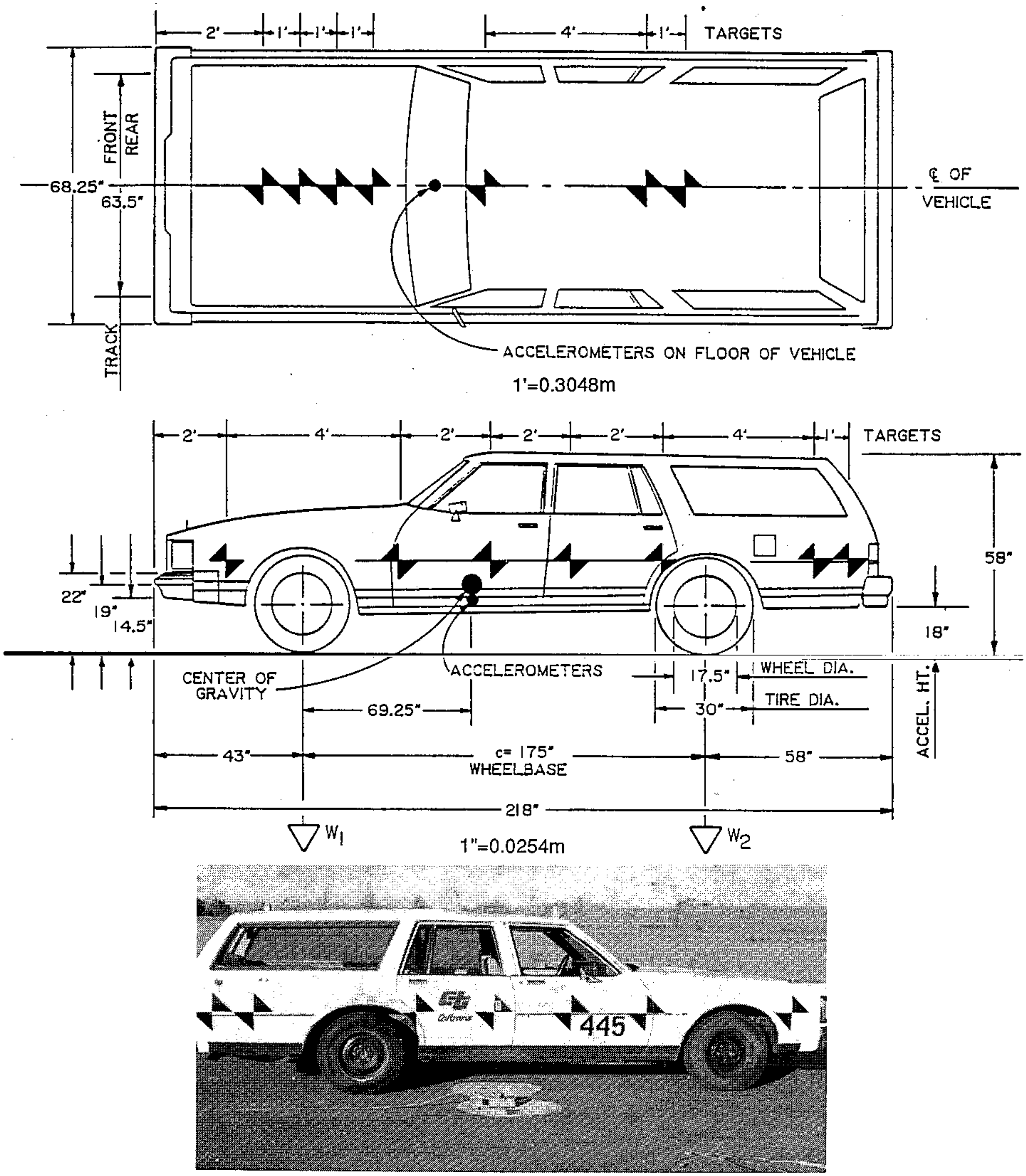
CAR DIMENSIONS

FIGURE A3



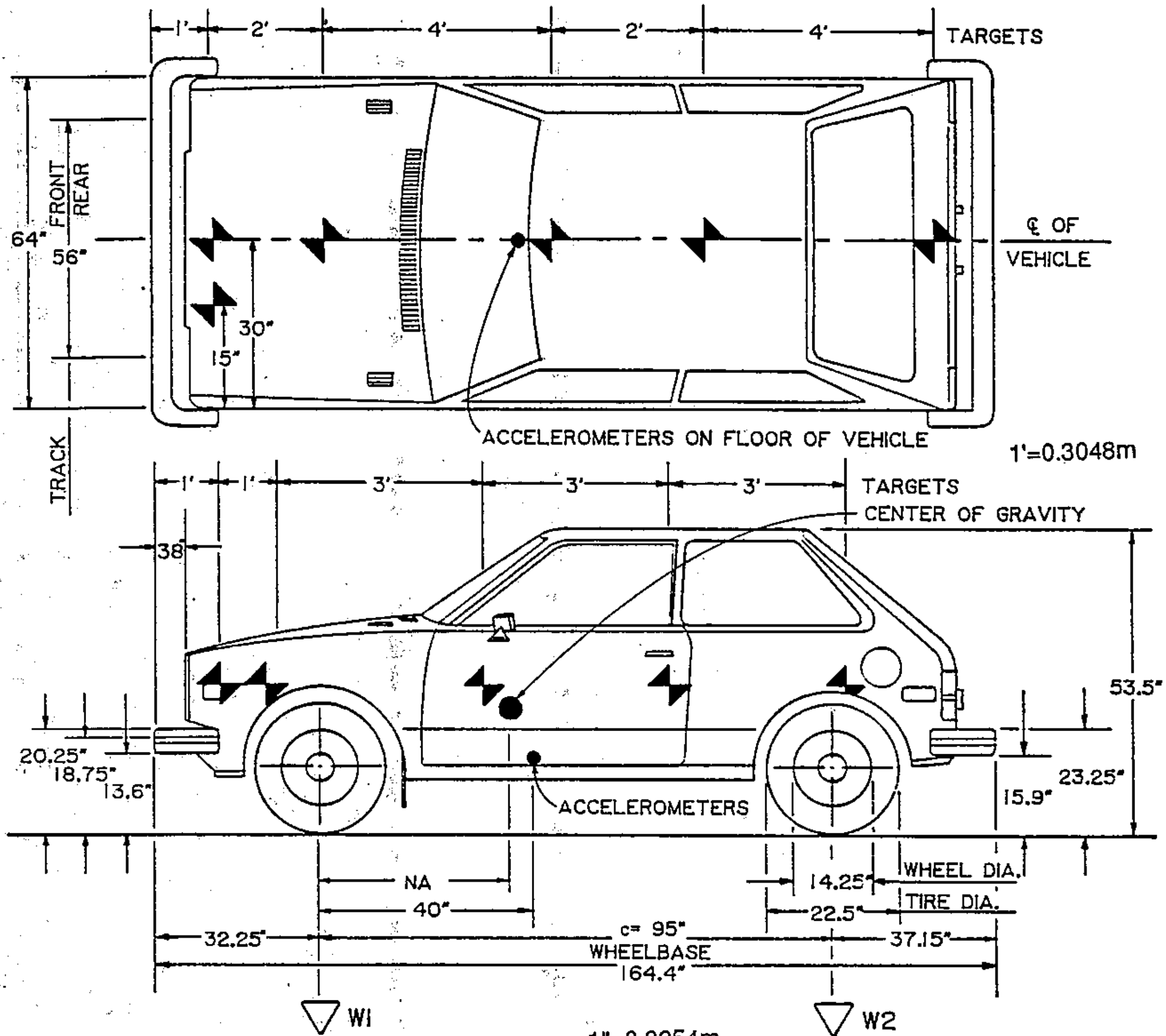
CAR DIMENSIONS

FIGURE A4



CAR DIMENSIONS

FIGURE A5



CAR DIMENSIONS

FIGURE A6

Several high-speed movie cameras recorded the impact during the crash tests. The types of cameras and their locations are shown in Figure B1.

All of these cameras were mounted on tripods except three cameras that were mounted on a 35-foot (10.7 m) high tower directly over the point of impact on the test barrier, and one high-speed camera that was mounted in the car to record the dummy's motions.

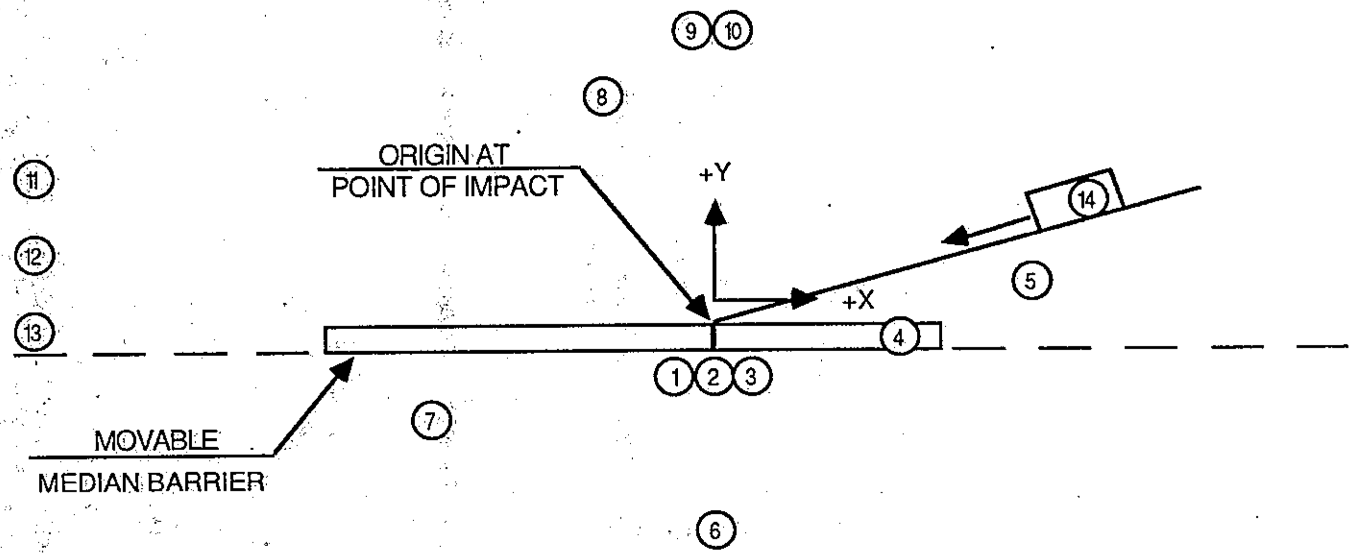
These cameras were connected by cables to a console trailer near the impact area which contained eight 12-volt batteries. Most of the cameras were turned on remotely from a control panel on the trailer. One camera was turned on directly by a crew member. The camera in the test vehicle was triggered by removing a "key" from a switch, mounted on the rear bumper. A tether line, anchored at one end, was attached to the key, and pulled it out after the car traveled 300 feet (191 m). The test vehicle and test barrier were photographed before and after impact with a normal speed movie camera, a black and white still camera and a color slide camera. A film report of this project has been assembled using edited portions of the movie coverage.

<u>Following are the pretest procedures that were required to enable film data reduction on a Vanguard Motion Analyzer:</u>

* Butterfly targets were attached to the top and sides of the test vehicles. The target locations are shown in Figures A1 through A6. The targets established scale factors and horizontal and vertical alignment. The test barrier was targeted with black and white tape also.

* Flashbulbs, mounted on the test vehicle, were electronically flashed to establish (a) initial vehicle to barrier contact, (b) the application of the vehicle brakes, and (c) beginning and end of sliding weight travel (on tests where sliding weight was used). The impact flashbulbs have a delay of several milliseconds before lighting up.

* Five tape switches, placed at 10-foot (3.05 m) intervals, were attached to the ground perpendicular to the path of the impacting vehicle near the barrier.Flash bulbs were activated sequentially when the tires of the test



Cam. No.	Film mm	Camera Type	Camera Rate: ft/sec.	Lens mm	Coordinates, ft. Test 441 X	Test 441 Y	Test 442 X	Test 442 Y	Test 443 X	Test 443 Y	Test 444 X	Test 444 Y	Test 445 X	Test 445 Y	Test 446 X	Test 446 Y
1	16	PHOTOSONICS	400	13	-1.5	0	-1.5	0	-1.5	0	-1.5	0	-1.5	0	-1.5	0
2	16	PHOTOSONICS	400	13	0	0	0	0	0	0	0	0	0	0	0	0
3	16	REDLAKE-LOCAM[1]	400	13	1.5	0	1.5	0	1.5	0	1.5	0	1.5	0	1.5	0
4	16	PHOTOTEC.	400	75	100	0			124	0	146	0	164	0	153	0
5	16	REDLAKE-LOCAM	400	75			103	4.5	191	3	167	NA	174	1.5	162	3
6	16	REDLAKE-LOCAM	400	13	-3	-32	-5	-35	0	-42						
7	16	REDLAKE-LOCAM	400	13	-89	-16	-87	-30	NA	-65	-82	-15	-75	-14.5	-58.5	-14
8	16	REDLAKE-LOCAM[1]	400	12	-96	68	-87	63	NA	-61	NA	70.5	NA	70.5	NA	70.5
9	16	BOLEX	24	25.4	0	-90	0	-99	0	89	0	90	0	89	0	89
10	16	REDLAKE-LOCAM	400	12	0	-90	0	-99	0	89	0	90	0	89	0	89
11	70	HULCHER	20	300	-280	NA	-182	NA	-150	20	-221	7.5	-208	6.5	-200	-4.5
12	35	HULCHER	20	200	-280	NA	-182	NA	-150	24	-221	5.5	-208	4.5	-200	3
13	16	REDLAKE-LOCAM[1]	400	25	-280	0	-182	0	-150	0	-221	3	-208	2.5	-200	1
14	16	PHOTOSONICS	200	7.5												

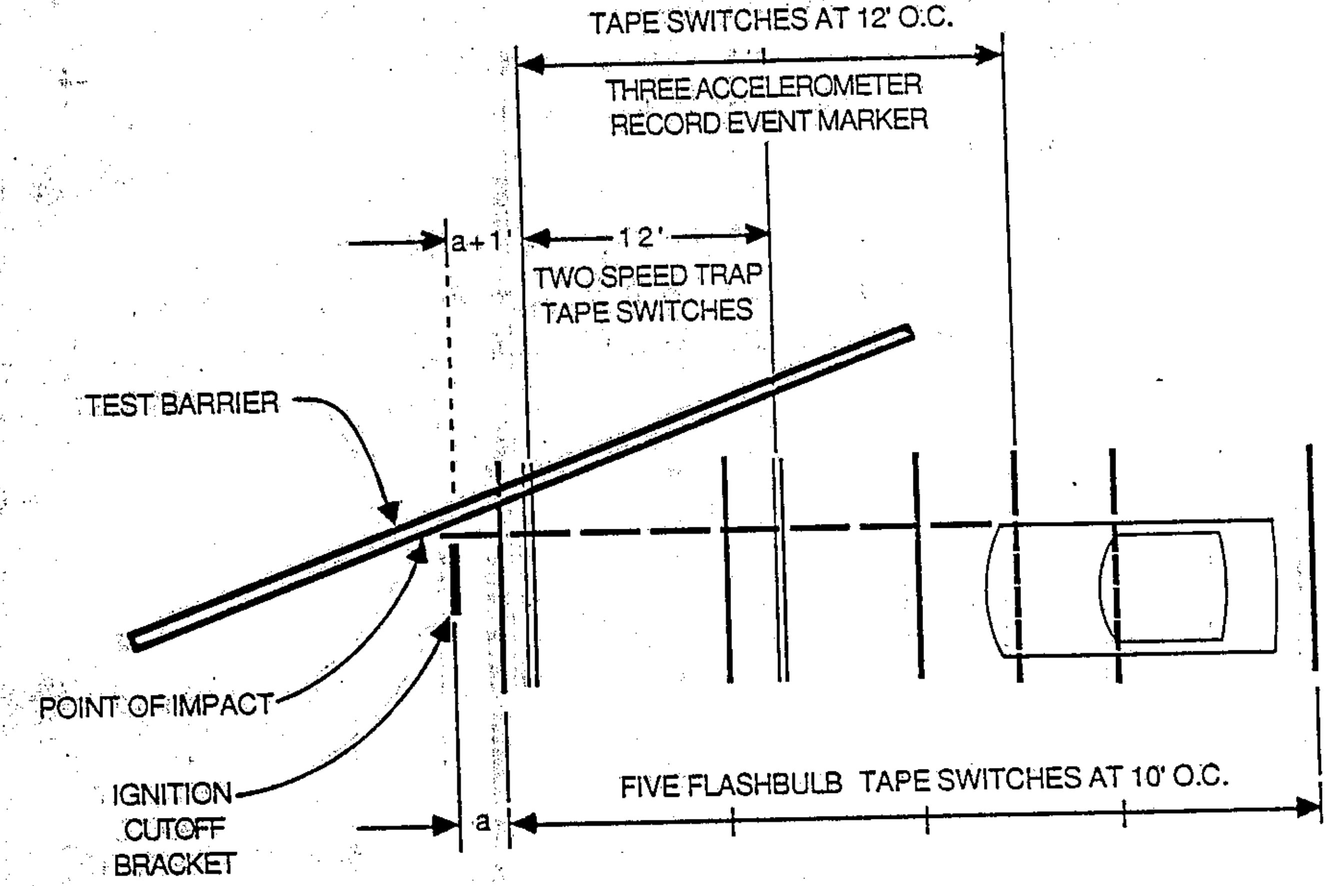
Notes:
1. In tests 441 and 442, Photosonics cameras were used.
2. All cameras were on tripods except 1,2, & 3 on a 35 ft. tower and 14 in the car (No car camera was used in tests 443 and 446). Cameras 9 and 10 panned the impacts.
3. The frame rate listed is the nominal value.

CAMERA LAYOUTS

FIGURE B1

vehicle rolled over the tape switches. The flashbulb stand was placed in view of most of the data cameras. The flashing bulbs were used to correlate the cameras with the impact events; and to calculate the impact speed independent of the electronic speed trap. The tape switch layout is shown in Figure B2.

* All high-speed cameras had timing light generators which exposed red timing pips on the film at a rate of 1000 per second. The pips were used to determine camera frame rates and to establish time-sequence relationships.



TEST NO.	441	442	443	444	445	446
a, ft.	1	1	1	2	1	2

1'=0.3048m

TAPE SWITCH LAYOUT
TESTS 441 THROUGH 446
FIGURE B2

Six accelerometers measured acceleration. Three unbonded strain gage accelerometers (Statham) were near the longitudinal and lateral center of gravity of the vehicles. One each was oriented in the longitudinal, lateral and vertical direction. These accelerometers were mounted on a small rectangular steel plate which was bolted to another steel bracket that was welded to the floorboard. Figures A1 through A6 show the location of these accelerometers. Table C1 gives information on the instrumentation. Figure C1 shows the sign conventions for the vehicle accelerometers. Three piezo-resistive accelerometers (Endevco) were mounted in the head cavity of the dummy. One each was oriented in the longitudinal, lateral and vertical direction.

Data from the accelerometers in the test vehicle were transmitted through a 1000-foot (304.8 m) Belden number 8776 umbilical cable connecting the vehicle to a 14 channel Hewlett Packard 3924C magnetic tape recording system. This recording system was in an instrumentation trailer at the test control area.

Three pressure-activated tape switches were placed on the ground in front of the test barrier. They were spaced at carefully measured intervals of 12 feet (3.66 m). When the test vehicle tires passed over them, the switches produced sequential impulses or "event blips" which were recorded concurrently with the accelerometer signals on the tape recorder and served as "event markers". A tape switch on the front bumper of the vehicle closed at the instant of impact and activated flash bulbs mounted on the vehicle. The closure of the bumper switch also put a "blip" or "event marker" on the recording tape. A time cycle was recorded continuously on the tape with a frequency of 500 cycles per second. The impact velocity of the vehicle could be determined from the tape switch impulses and timing cycles. Two other tape switches connected to digital readout equipment were placed 12 feet (3.66 m) apart just upstream from the test barrier specifically to determine the impact speed of the test vehicle immediately after the test. The tape switch layouts are shown in Appendix B in Figure B2.

After the test, the accelerometer data were played back from the tape recorder through a Visicorder which produced an oscillographic trace (line) on paper for each channel of the tape. Each paper record contained a curve of data from one

TABLE C1 - ACCELEROMETER DATA

Type	Location	Range	Orientation	Test number
Statham	Vehicle c.g.	100g	Longitudinal	All
Statham	Vehicle c.g.	100g	Lateral	All
Sratham	Vehicle c.g.	100g	Vertical	441,442
Statham	Vehicle c.g.	50g	Vertical	443 thru 446
Humphrey	Vehicle c.g.	180°/sec	Roll	All
Humphrey	Vehicle c.g.	90°/sec	Pitch	All
Humphrey	Vehicle c.g.	180°/sec	Yaw	All
Endevco	Dummy's head	200g	Longitudinal	All
Endevco	Dummy's head	200g	Lateral	All
Endevco	Dummy's head	200g	Vertical	All

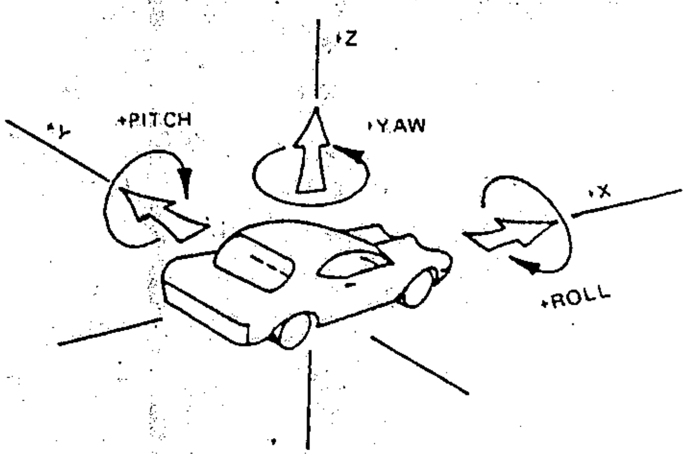


FIGURE C1. VEHICLE ACCELERATION SIGN CONVENTION accelerometer, signals from the event marker tape switches and bumper impact switch, and the time cycle markings.

Some of the data from the accelerometers mounted on the test vehicle contained high frequency spikes. All the test vehicle data were filtered at 100 hertz and 12 db per octave cutoff with a Krohn-Hite filter to facilitate data interpretation and reduction by hand. The smoother resultant curves gave a good representation of the overall acceleration of the vehicle without significantly altering the amplitude and time values of the acceleration pulses. The data from the accelerometers in the dummy's head were smoother and were not filtered.

The Visicorder paper records of accelerometer data served as a check on the main data reduction method described below.

All accelerometer data were processed on a Norland Model 3001 waveform analyzer which was the primary means of data reduction. The analyzer digitized and manipulated the raw data, printed test results, and plotted various curves. In addition to the above for tests 443 and 445, three additional piezo-resistive (Endevco) accelerometers were mounted near the vehicle center of gravity and recorded on a new Pacific Instruments digital data recorder (PACDAS) which was mounted in the vehicle. These data were reduced using a microcomputer.

The data curves are shown in Figures C2 through C15 and include the accelerometer records from the vehicle and dummy for Tests 441 through 446. All curves were calculated using the Norland analyzer except for C7 and C12 which were obtained using PACDAS.

Figures C16 through C23 show plots of the longitudinal components of velocity vs time and longitudinal displacement vs time for Tests 441 through 446. All curves were obtained using Norland Analyzer except for C19 and C22 which were obtained using PACDAS. These plots were needed to calculate the occupant impact velocity defined in Reference 2.

The occupant impact velocity is theoretical; however, on the plot of distance vs time, the curves can be visualized as representing the car windshield and the driver's head. It is assumed that the head starts out two feet (0.6 m) behind the windshield. The point where the curves cross represents the impact between the head and the windshield because the windshield has slowed down from the impact velocity, but the head has not. The time when the windshield/head impact occurs (rattle space time) is carried to the plot of velocity vs time. The occupant impact velocity is the difference between the vehicle impact velocity and the vehicle velocity at the end of the rattle space time.

The dummy accelerometers are not used in determining the occupant impact velocity, only the vehicle accelerometers.

Rate gyros were mounted next to the vehicle accelerometers. They measured the rate of angular change (angular velocity) of the vehicle in the roll, pitch, and yaw directions. Figure C1 shows the sign convention for the rate gyros. The data from these transducers were transmitted on the same umbilical cable as the vehicle and dummy accelerometers. The rate gyro data were integrated to obtain a curve of angle position versus time after impact so the maximum value of roll, pitch and yaw could be determined.

FIGURE C2. TEST 441 - VEHICLE ACCELERATIONS

TEST NUMBER
441.00
MOVABLE
MEDIAN
BARRIER

JUNE 21 1985

MAX. 50 MS
AVER. ACCEL.
FOR CAR (G)-

VERTICAL---
2.8509
FROM TIME(S)
.27400

LONGITUDINAL
-3.5902
FROM TIME(S)
.19400

LATERAL
-4.1021
FROM TIME(S)
1.8500E-02

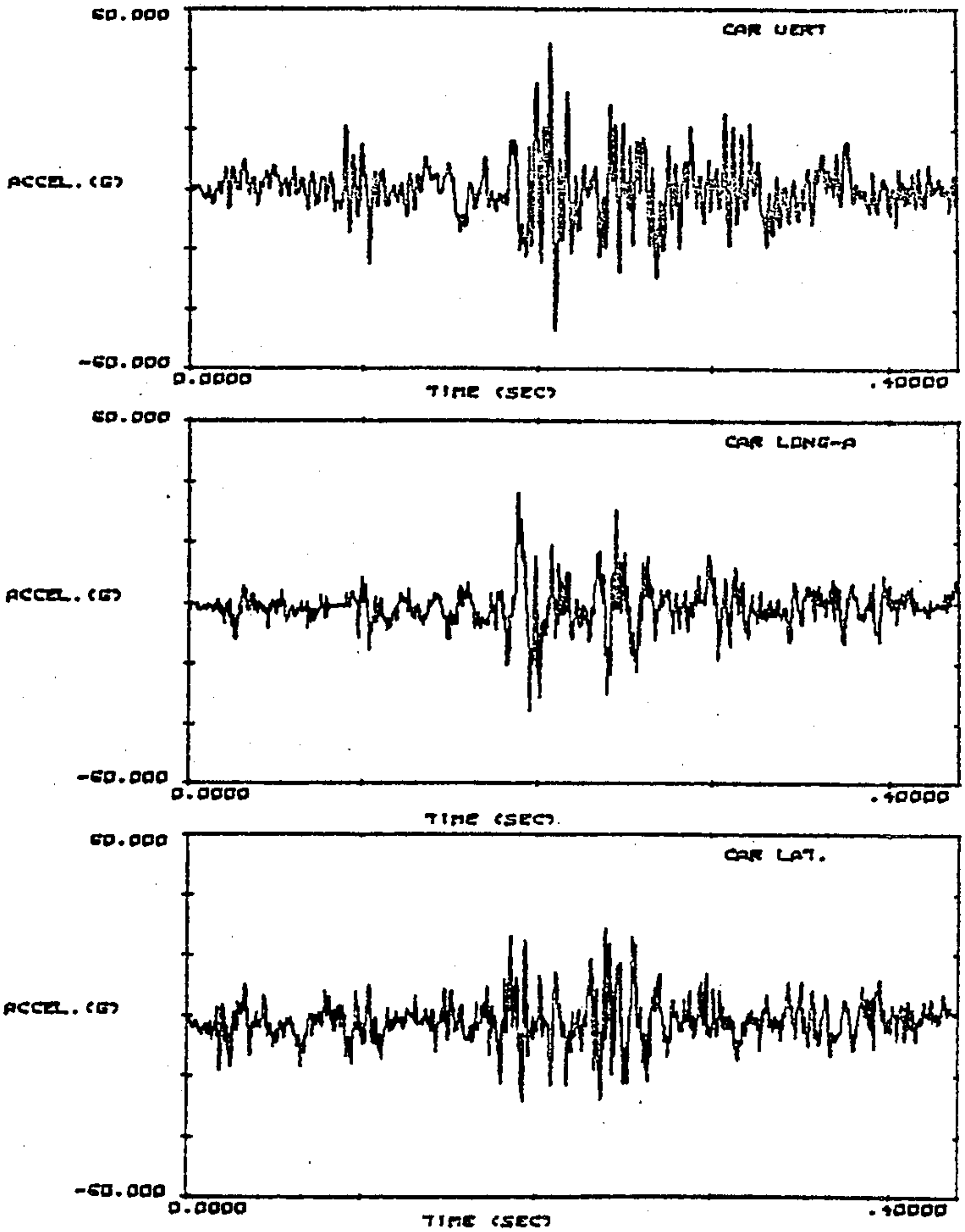


FIGURE C3. TEST 441 - DUMMY HEAD ACCELERATIONS

TEST NUMBER
441.00
MOVABLE
MEDIAN
BARRIER
15 DEGREES

JUNE 21 1985

MAXIMUM
50 MS AVER.
DUMMY HEAD
RESULTANT
ACCEL. (G)-
8.3600
FROM TIME(S)
.13200
TO TIME(S)
.18200

HEAD INJURY
CRITEREON-
36.449
FROM TIME(S)
.12950
TO TIME(S)
.42900

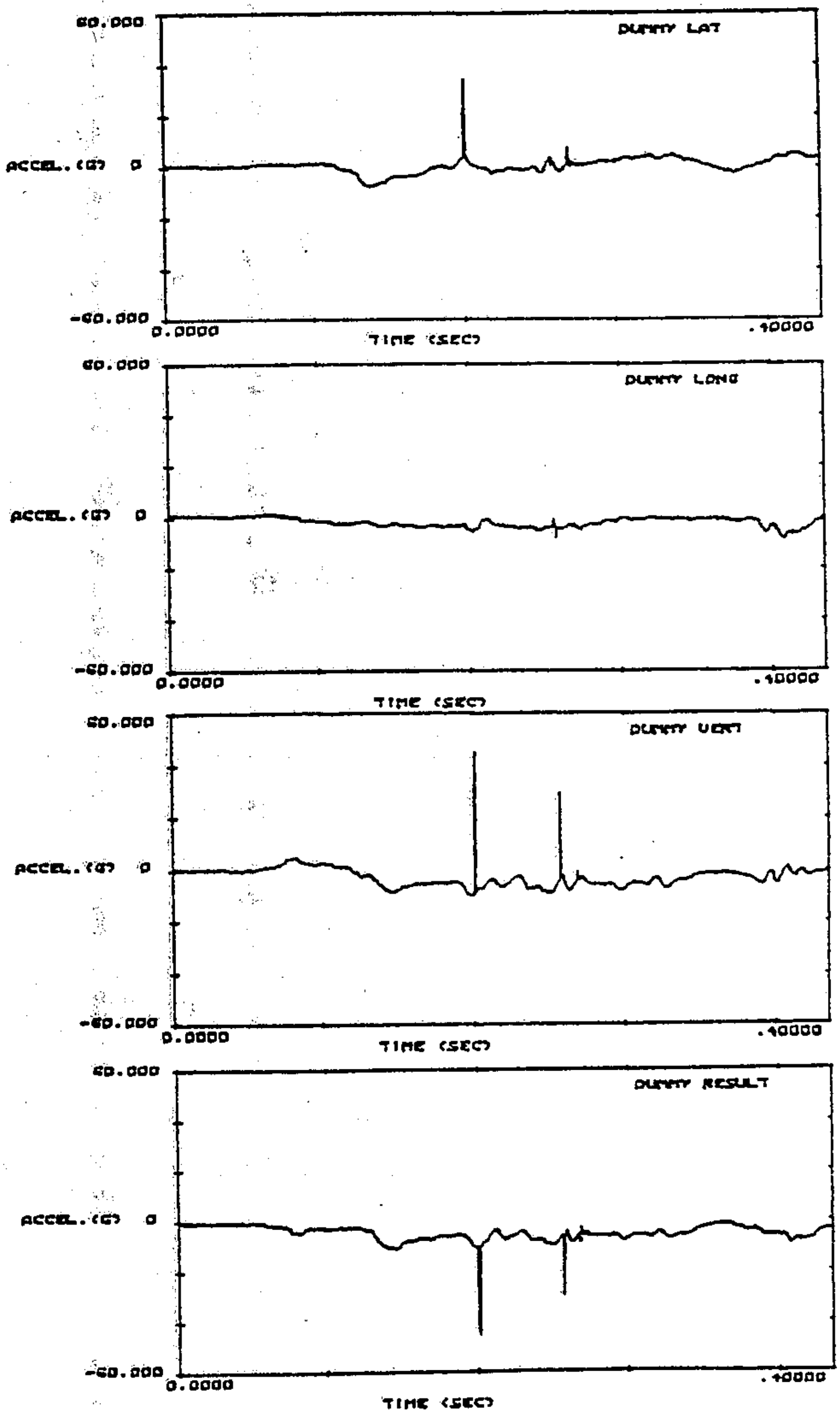


FIGURE C4. TEST 442 - VEHICLE ACCELERATIONS

TEST NUMBER

442.00

MOVABLE

MEDIAN

BARRIER

JULY 2 1985

MAX. 50 MS

AVER. ACCEL.

FOR CAR (G)-

VERTICAL---

4.4650

FROM TIME(S)

.24400

LONGITUDINAL

-7.7101

FROM TIME(S)

4.7500E-02

LATERAL

-8.1139

FROM TIME(S)

4.1500E-02

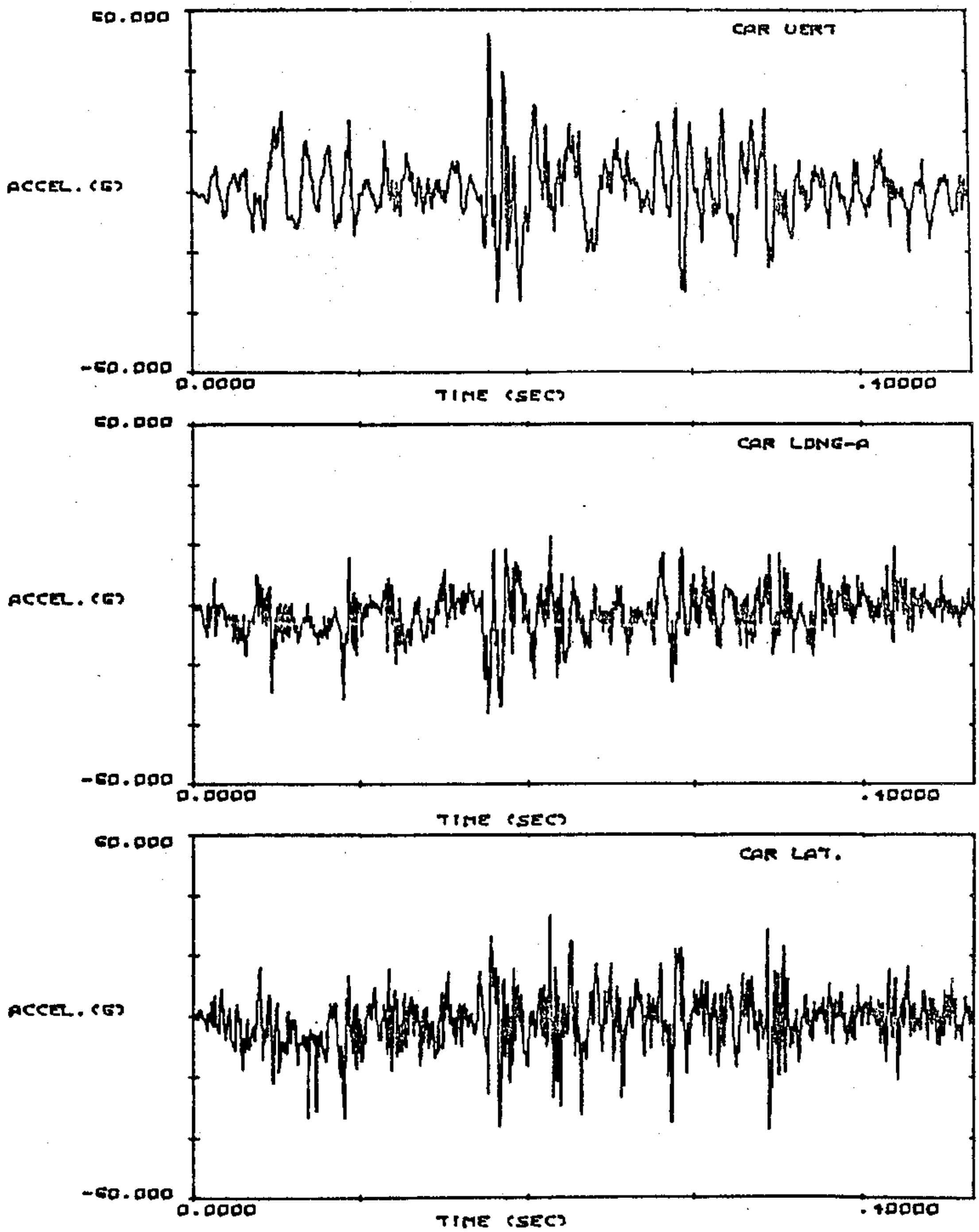


FIGURE C5. TEST 442 - DUMMY HEAD ACCELERATIONS

TEST NUMBER
442.00
MOVABLE
MEDIAN
BARRIER
25 DEGREES

JULY 2 1985

MAXIMUM
50 MS AVER.
DUMMY HEAD
RESULTANT
ACCEL. (G)-
21.873
FROM TIME(S)
.19300
TO TIME(S)
.24300

HEAD INJURY
CRITEREON-
122.51
FROM TIME(S)
.18450
TO TIME(S)
.24800

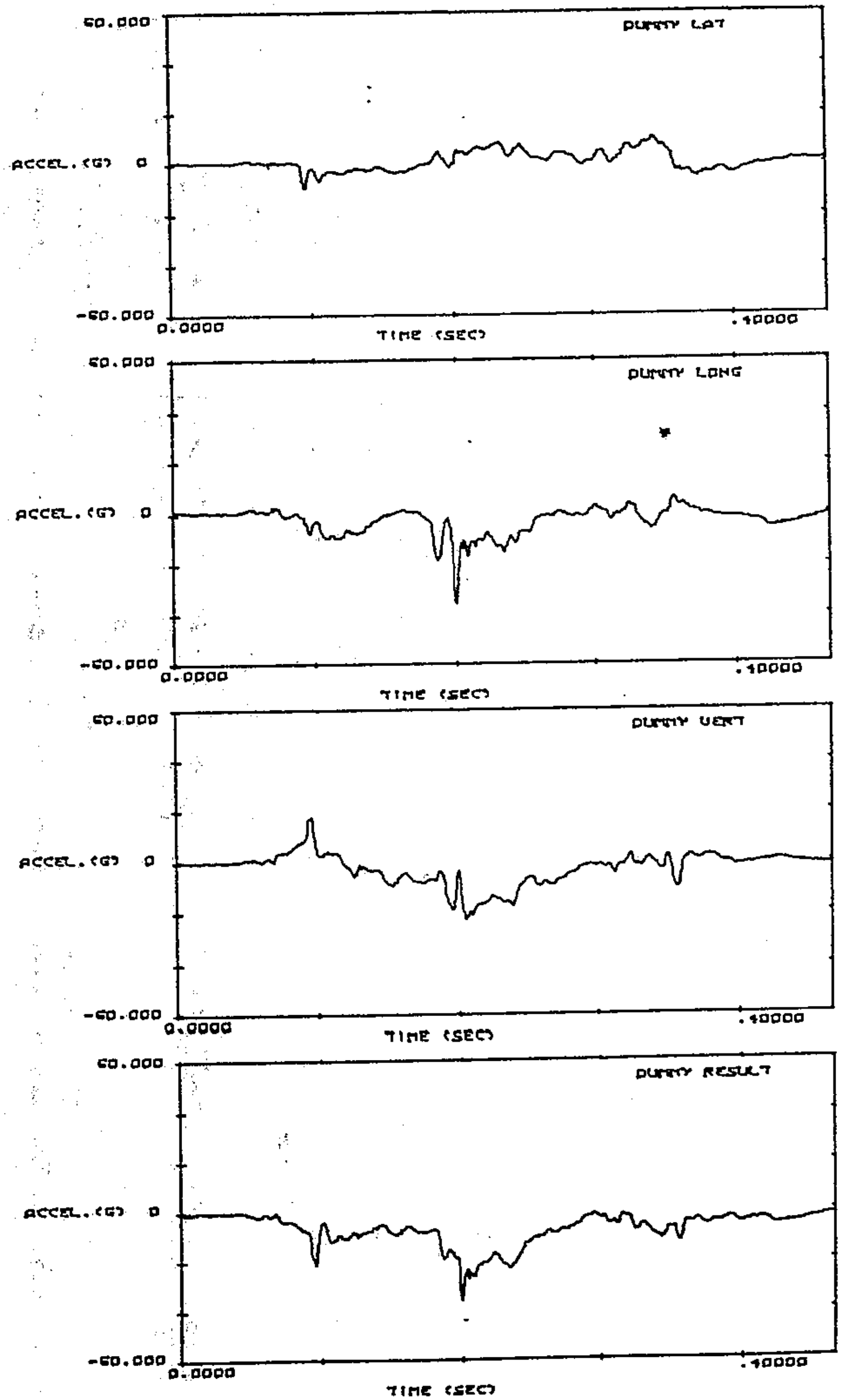


FIGURE C6. TEST 443 - VEHICLE ACCELERATIONS

TEST NUMBER

443.00

MOVABLE

MEDIAN

BARRIER

NOV. 18 1987

MAX. 50 MS

AVER. ACCEL.

FOR CAR (G)-

VERTICAL---

-2.0377

FROM TIME(S)

6.5500E-02

LONGITUDINAL

-8.2563

FROM TIME(S)

5.2000E-02

LATERAL

-7.7061

FROM TIME(S)

5.0500E-02

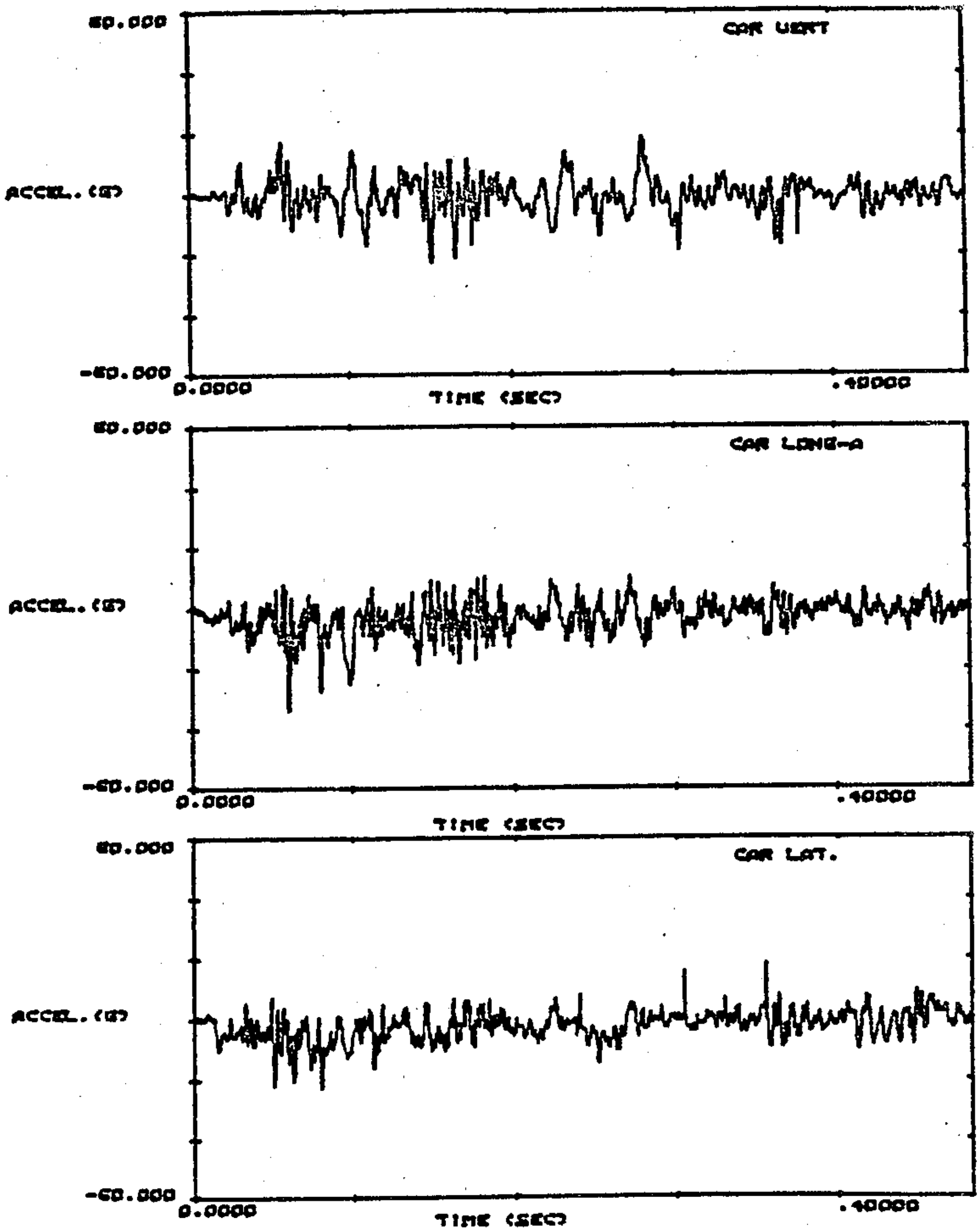


FIGURE C7. TEST 443 - VEHICLE ACCELERATIONS (PACDAS DATA)

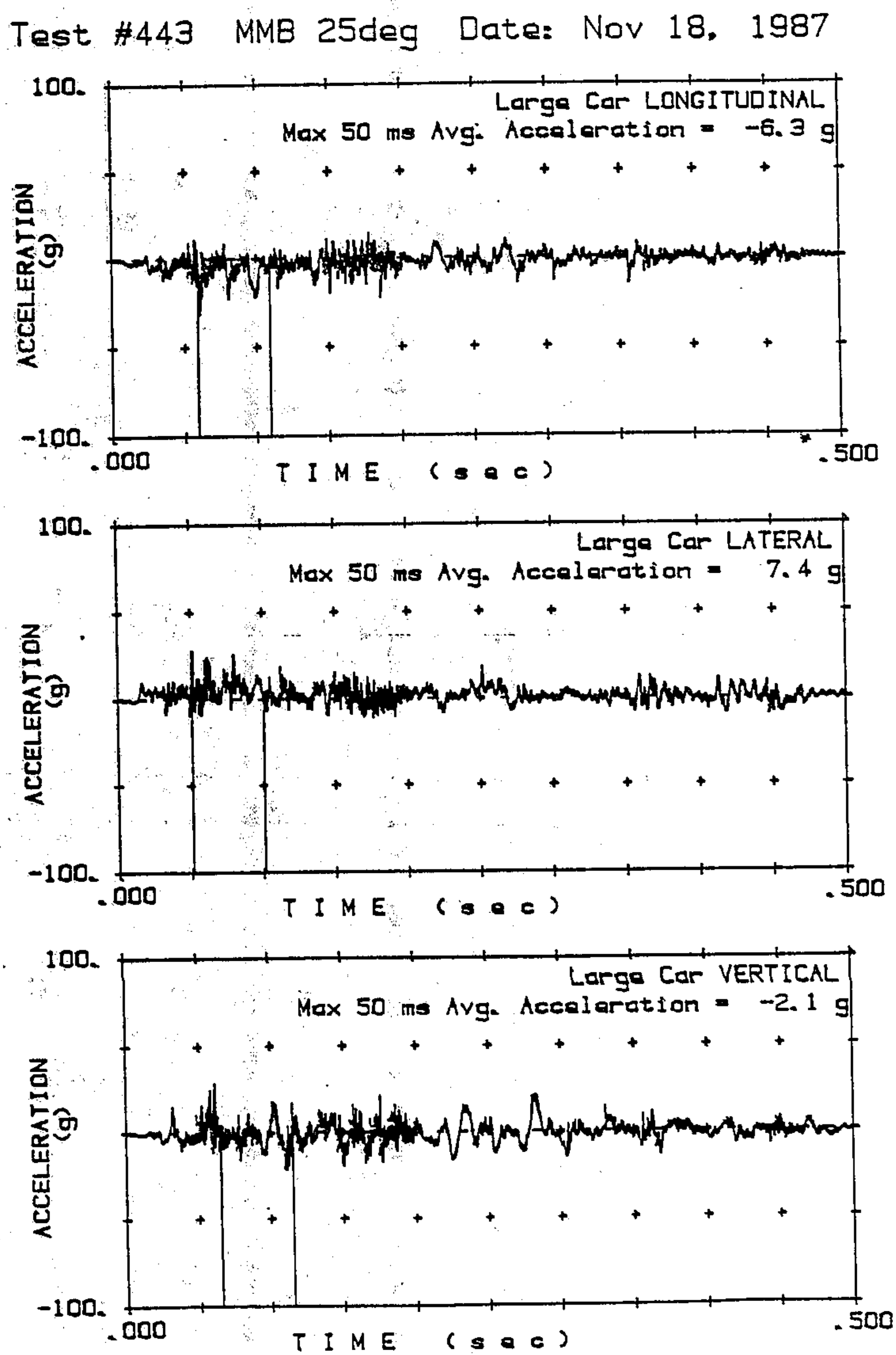


FIGURE C8. TEST 443 - DUMMY HEAD ACCELERATIONS

TEST NUMBER
443.00
MOVABLE
MEDIAN
BARRIER
25 DEGREES

NOV. 18 1987

MAXIMUM
50 MS AVER.
DUMMY HEAD
RESULTANT
ACCEL. (G)-
17.122
FROM TIME(S)
.19100
TO TIME(S)
.24100

HEAD INJURY
CRITEREON-
121.29
FROM TIME(S)
.11000
TO TIME(S)
.34250

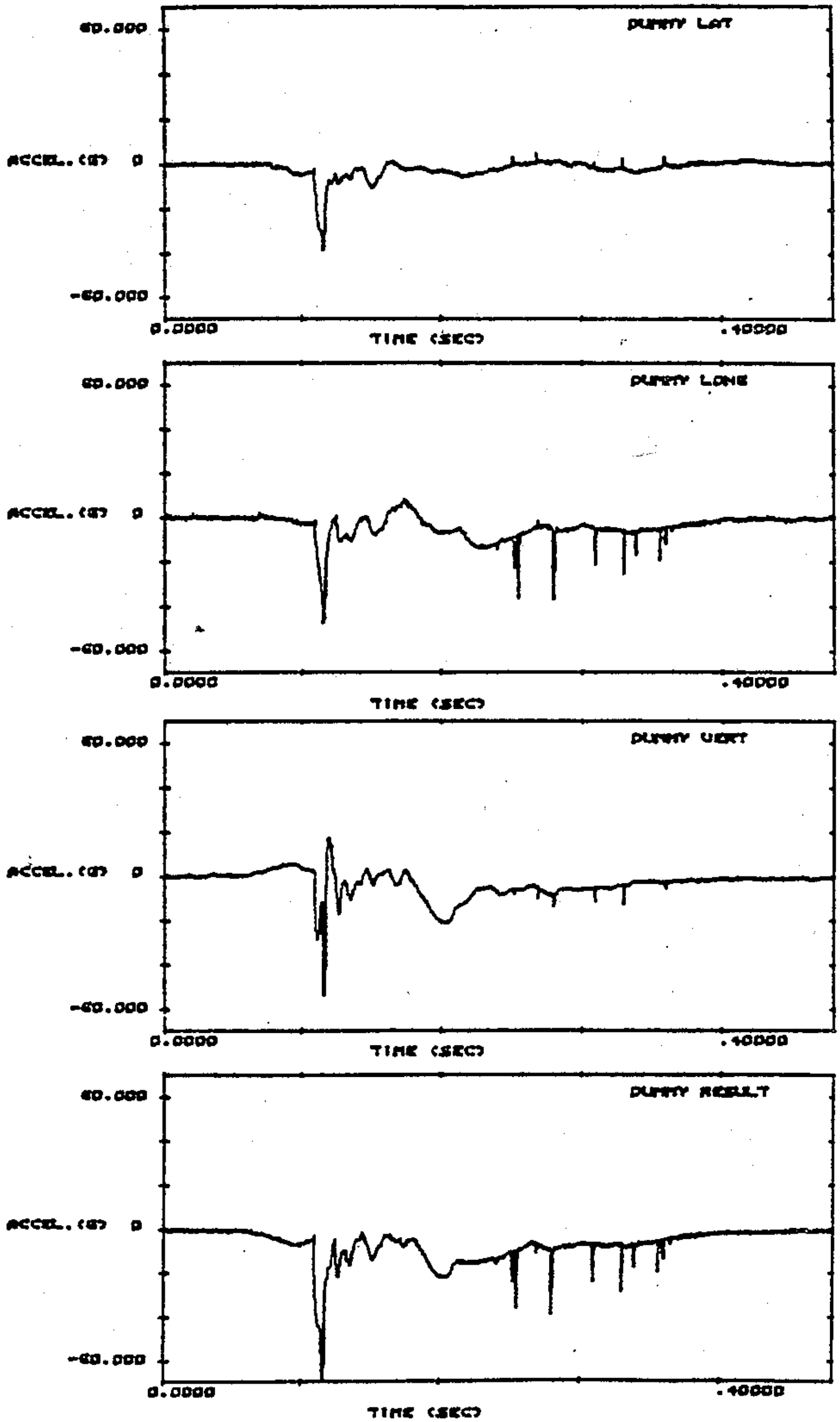


FIGURE C9. TEST 444 - VEHICLE ACCELERATIONS

TEST NUMBER
444.00
MOVABLE
MEDIAN
BARRIER

DEC. 18 1987

MAX. 50 MS
AVER. ACCEL.
FOR CAR (G)-

VERTICAL---
1.6920
FROM TIME(S)
.18650

LONGITUDINAL
-4.5508
FROM TIME(S)
1.8500E-02

LATERAL
-6.6669
FROM TIME(S)
2.9000E-02

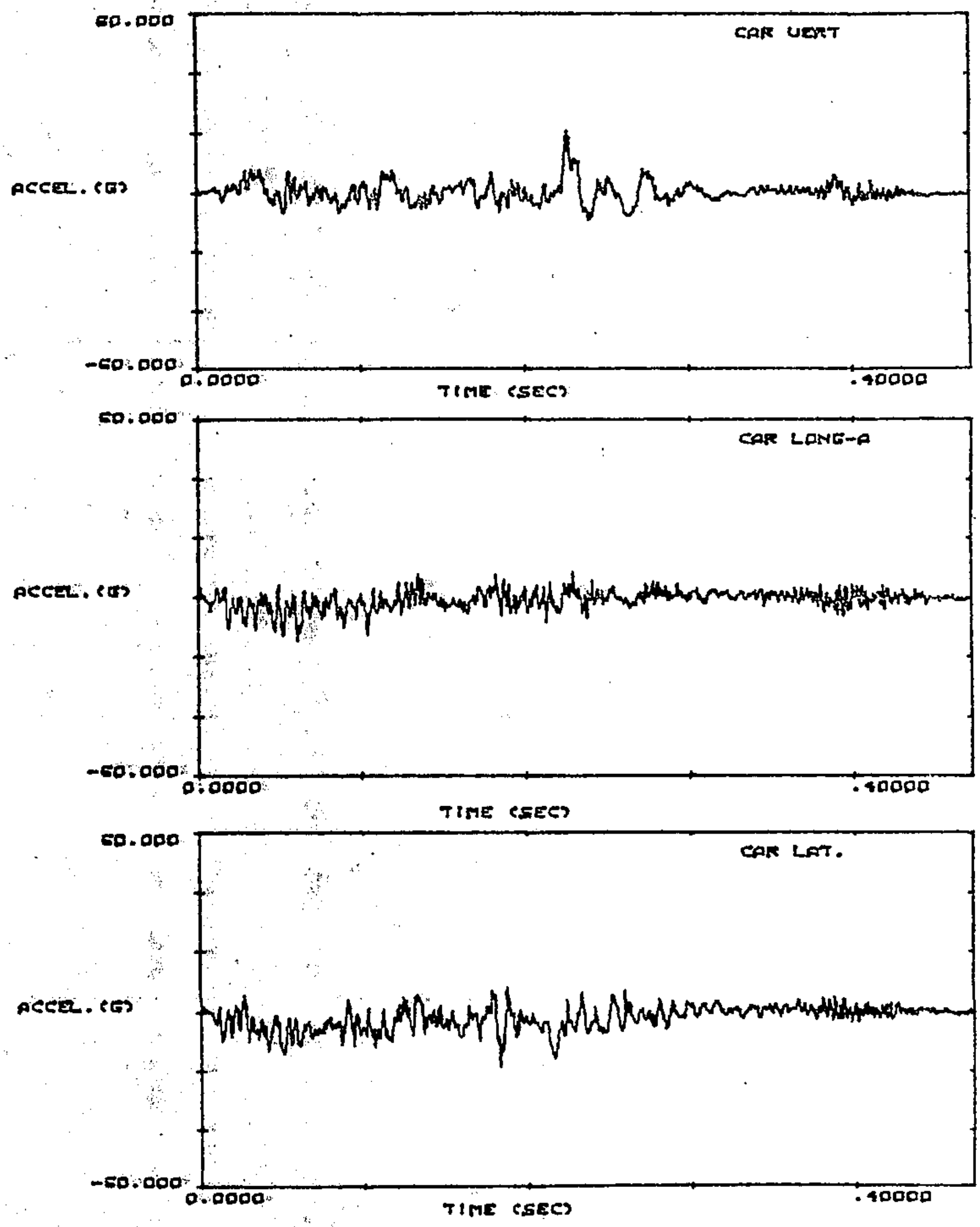


FIGURE C10. TEST 444 - DUMMY HEAD ACCELERATIONS

TEST NUMBER
444.00
MOVABLE
MEDIAN
BARRIER
15 DEGREES

DEC. 18 1987

MAXIMUM
50 MS AVER.
DUMMY HEAD
RESULTANT
ACCEL. (G)-
10.392
FROM TIME(S)
8.7000E-02
TO TIME(S)
.13700

HEAD INJURY
CRITEREON-
30.190
FROM TIME(S)
5.4000E-02
TO TIME(S)
.48000

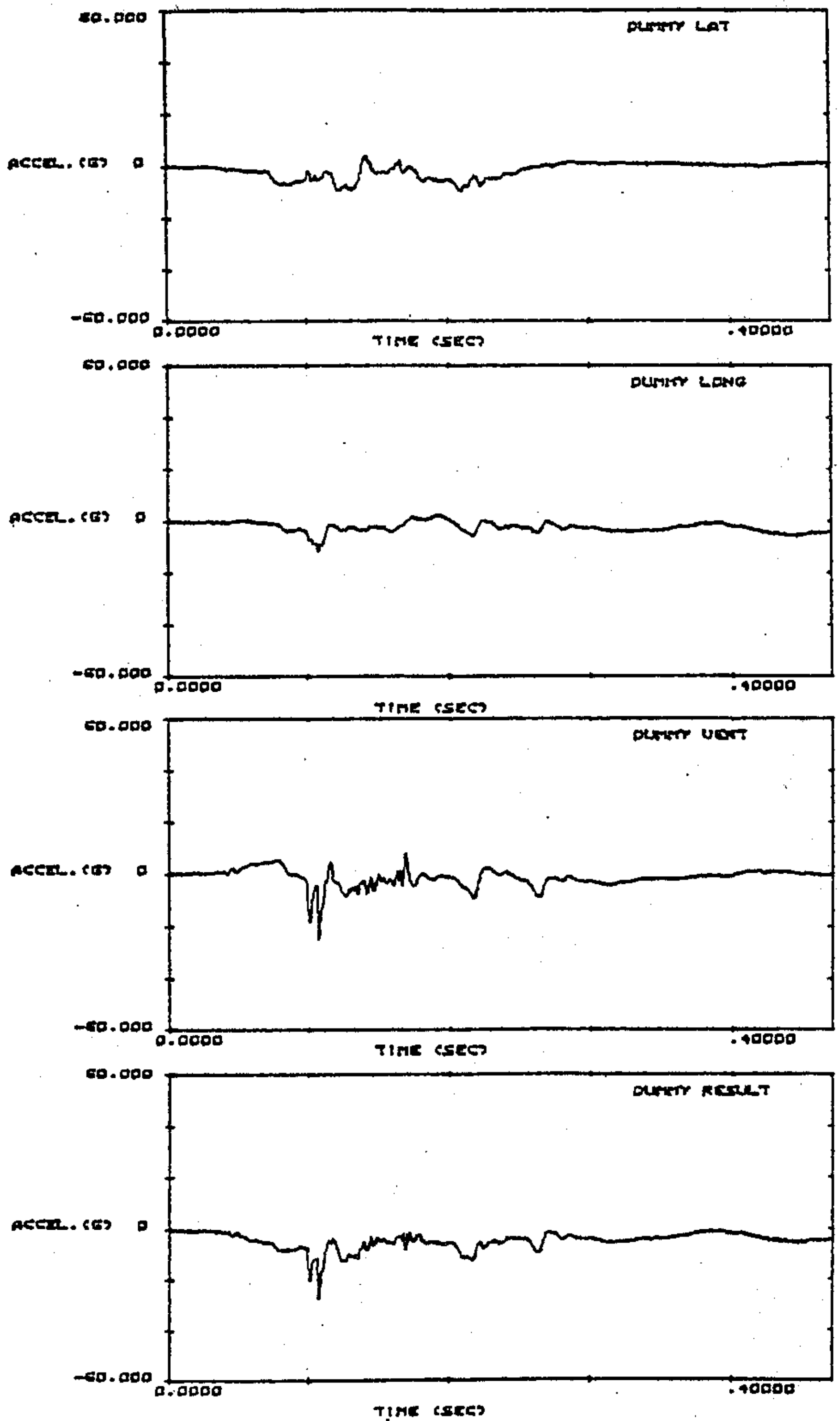


FIGURE C11. TEST 445 - VEHICLE ACCELERATIONS

TEST NUMBER
445.00
MOVABLE
MEDIAN
BARRIER

JAN. 21 1988

MAX. 50 MS
AVER. ACCEL.
FOR CAR (G)-

VERTICAL---
-1.6517
FROM TIME(S)
.23800

LONGITUDINAL
-3.2785
FROM TIME(S)
4.6000E-02

LATERAL
-5.8931
FROM TIME(S)
.15750

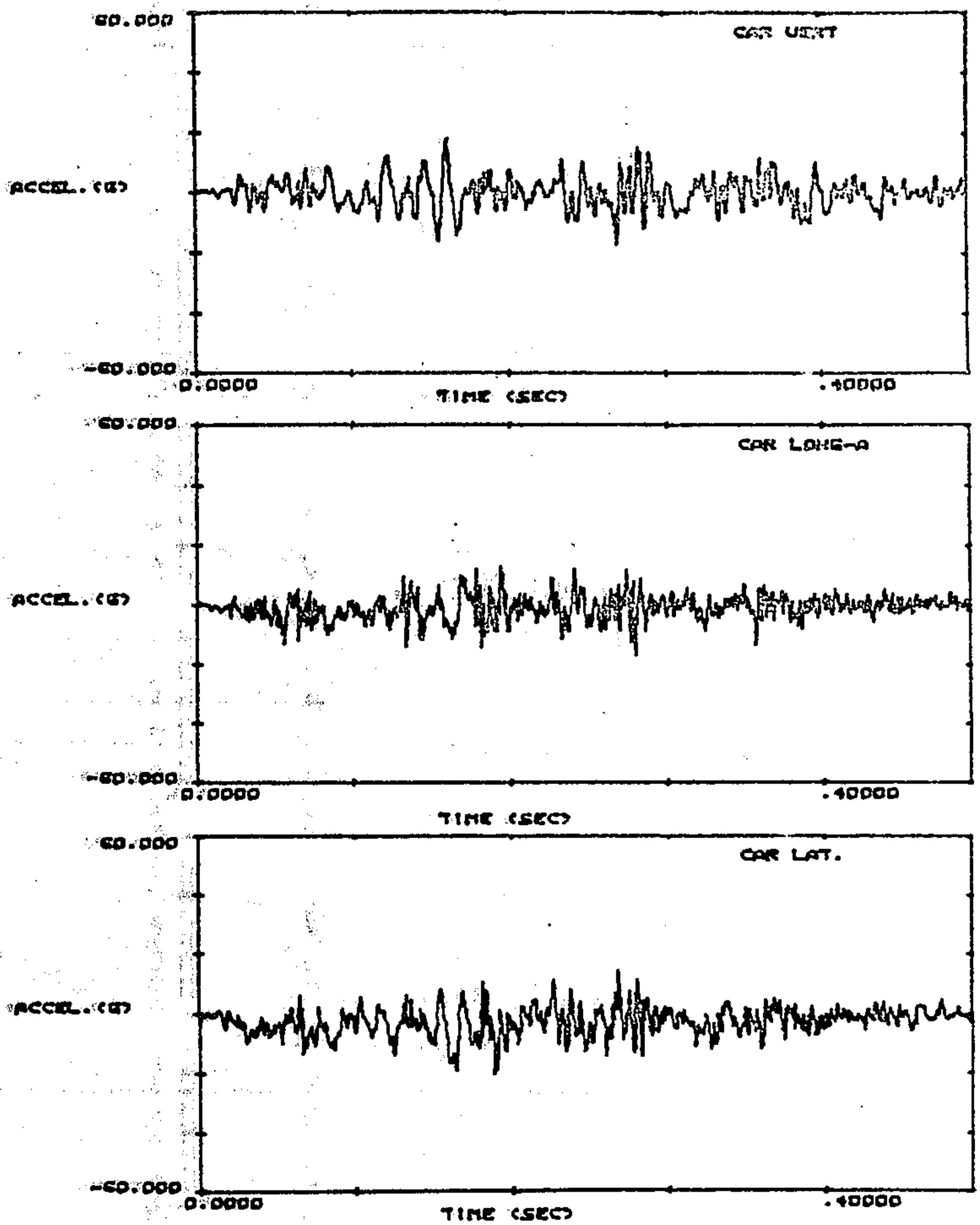


FIGURE C12. TEST 445 - VEHICLE ACCELERATIONS (PACDAS DATA)

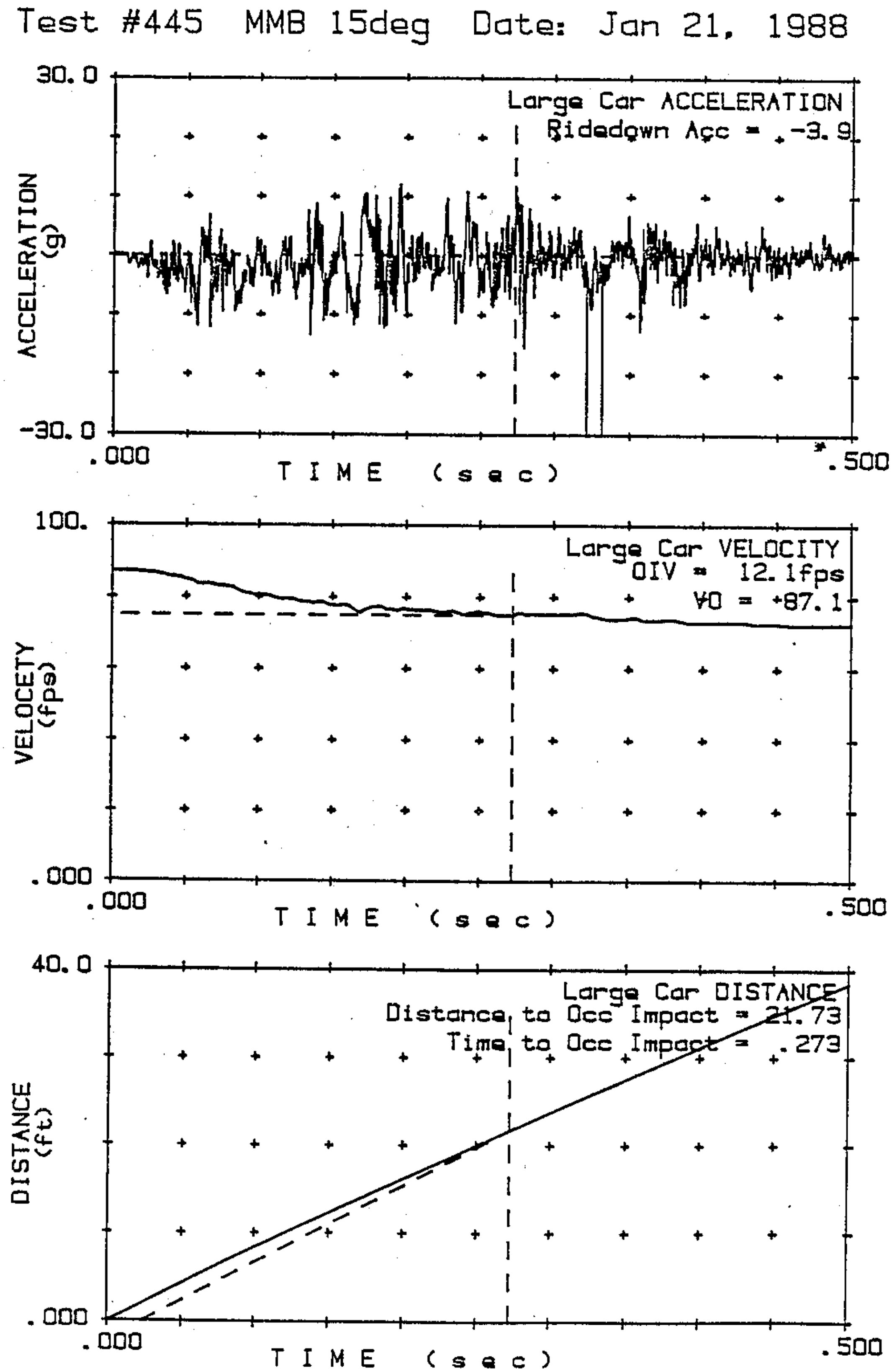


FIGURE C13. TEST 445 - DUMMY HEAD ACCELERATIONS

TEST NUMBER
445.00
MOVABLE
MEDIAN
BARRIER
15 DEGREES

JAN. 21 1988

MAXIMUM
50 MS AVER.
DUMMY HEAD
RESULTANT
ACCEL. (G)-
14.770
FROM TIME(S)
9.2000E-02
TO TIME(S)
.14200

HEAD INJURY
CRITEREON-
44.966
FROM TIME(S)
8.6500E-02
TO TIME(S)
.36000

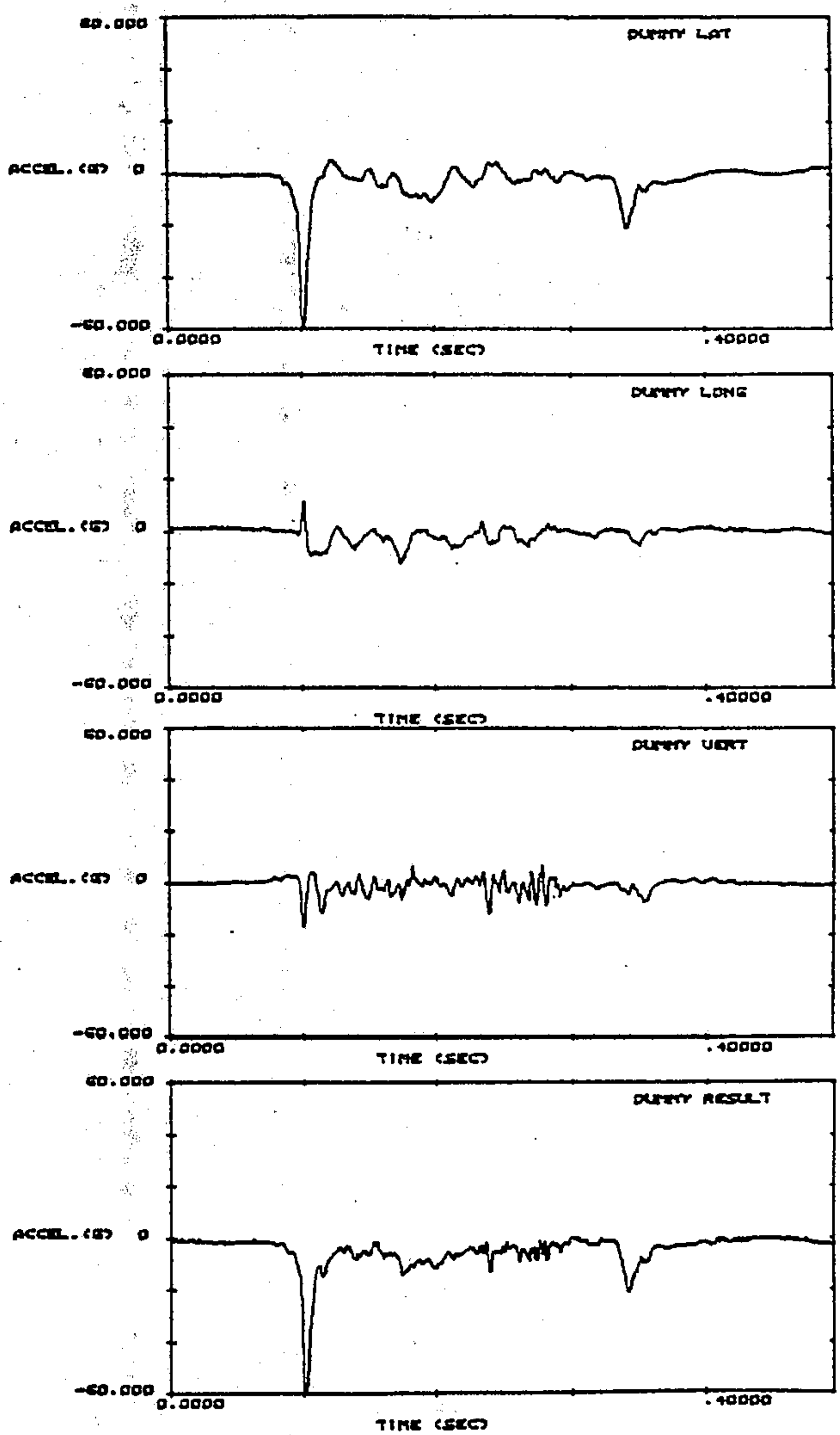


FIGURE C14. TEST 446 - VEHICLE ACCELERATIONS

TEST NUMBER
446.00
MOVABLE
MEDIAN
BARRIER

MARCH 9 1988

MAX. 50 MS
AVER. ACCEL.
FOR CAR (G)-

VERTICAL---
2.7934
FROM TIME(S)
0.0000

LONGITUDINAL
-7.5775
FROM TIME(S)
4.2000E-02

LATERAL
-11.297
FROM TIME(S)
3.6500E-02

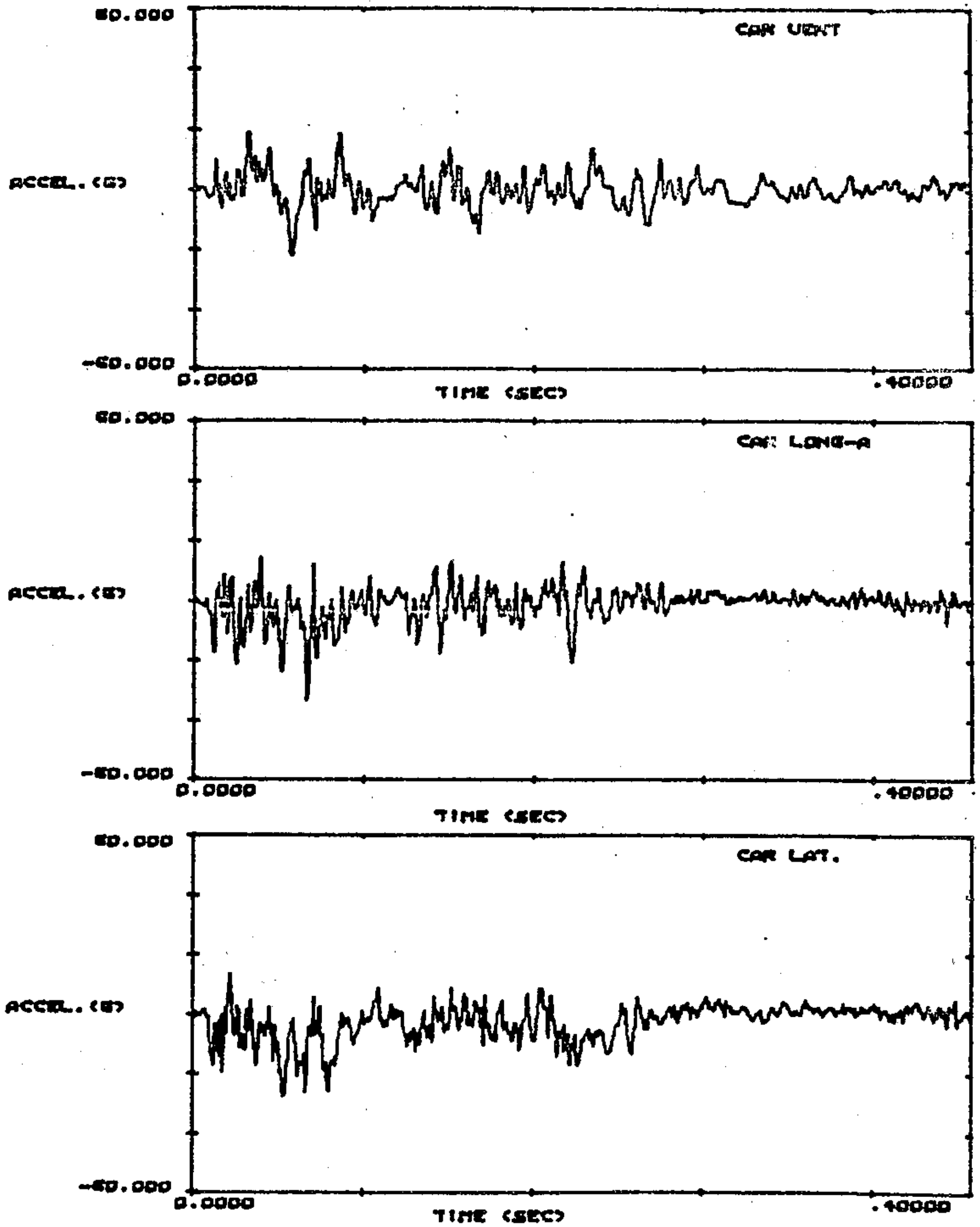


FIGURE C15. TEST 446 - DUMMY HEAD ACCELERATIONS

TEST NUMBER
446.00
MOVABLE
MEDIAN
BARRIER
15 DEGREES

MARCH 9 1988

MAXIMUM
50 MS AVER.
DUMMY HEAD
RESULTANT
ACCEL. (G)-
14.050
FROM TIME(S)
.20150
TO TIME(S)
.25150

HEAD INJURY
CRITEREON-
86.288
FROM TIME(S)
.10000
TO TIME(S)
.38950

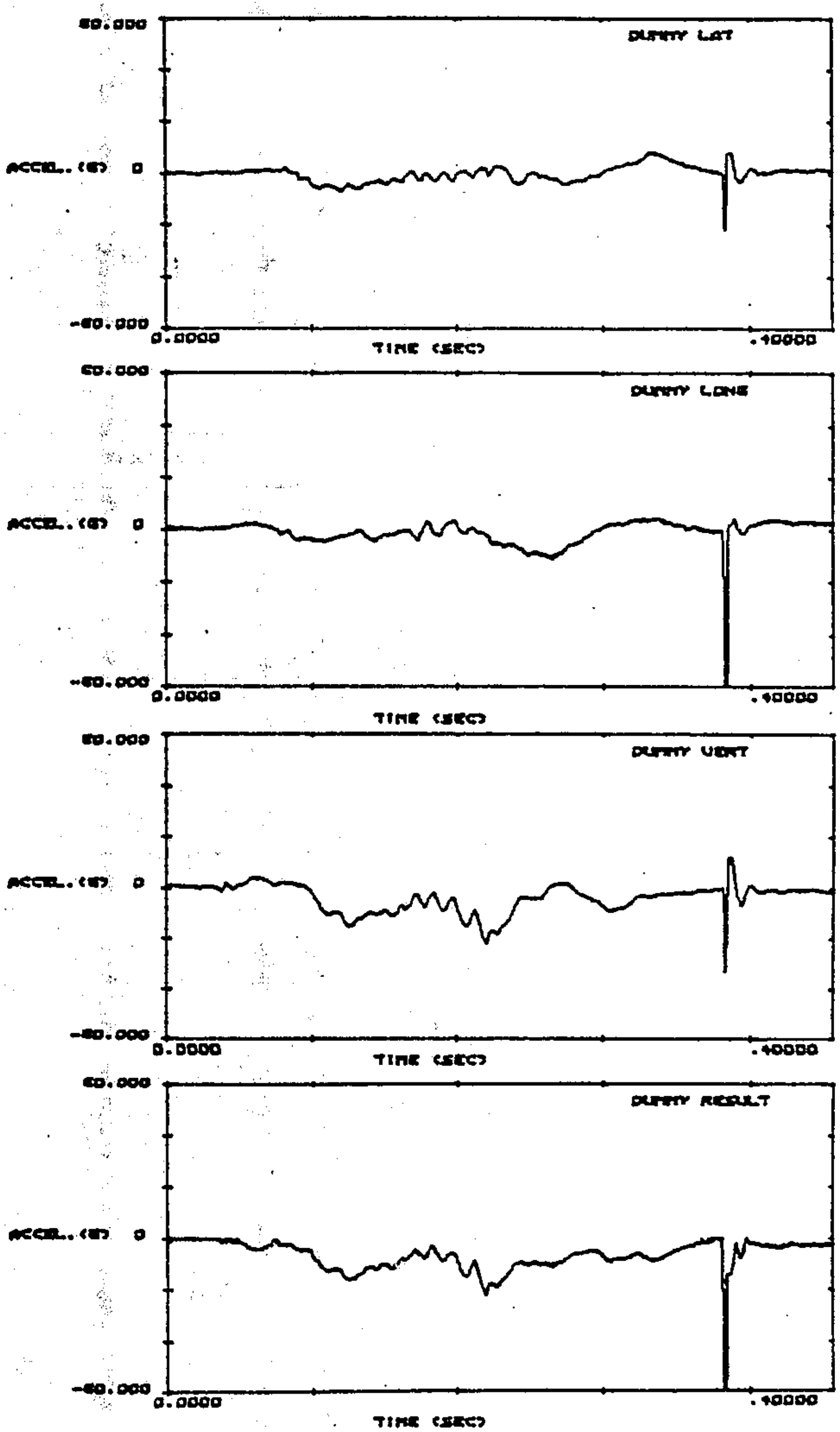


FIGURE C16. TEST 441 - VEHICLE LONGITUDINAL VELOCITY AND DISPLACEMENT VS. TIME

TEST NUMBER
441.00
MOVABLE
MEDIAN
BARRIER

JUNE 21 1985

CAR IMPACT
VELOCITY
(FPS)-
86.973

AT CAR
DISTANCE(FT)
19.352
OCCUPANT
IMPACT
OCCURS

OCCUPANT
IMPACT
VELOCITY
(FPS)-
15.461
OCCURS AT
.24550
SEC. AFTER
CAR IMPACT

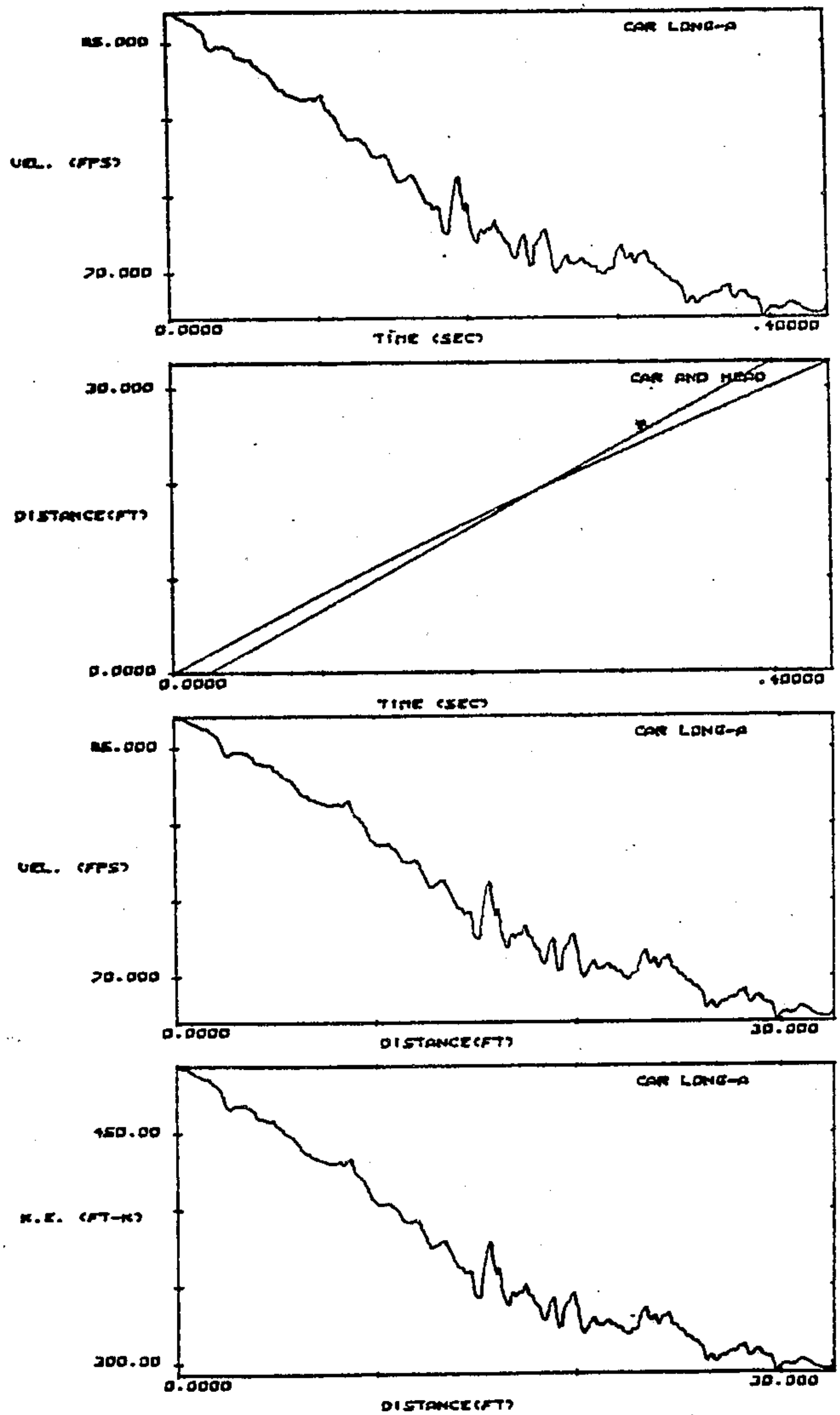


FIGURE C17. TEST 442 - VEHICLE LONGITUDINAL VELOCITY AND DISPLACEMENT VS. TIME

TEST NUMBER
442.00
MOVABLE
MEDIAN
BARRIER

JULY 2 1985

CAR IMPACT
VELOCITY
(FPS)-
30.787

AT CAR
DISTANCE(FT)
12.297
OCCUPANT
IMPACT
OCCURS

OCCUPANT
IMPACT
VELOCITY
(FPS)-
24.684
OCCURS AT
.15750
SEC. AFTER
CAR IMPACT

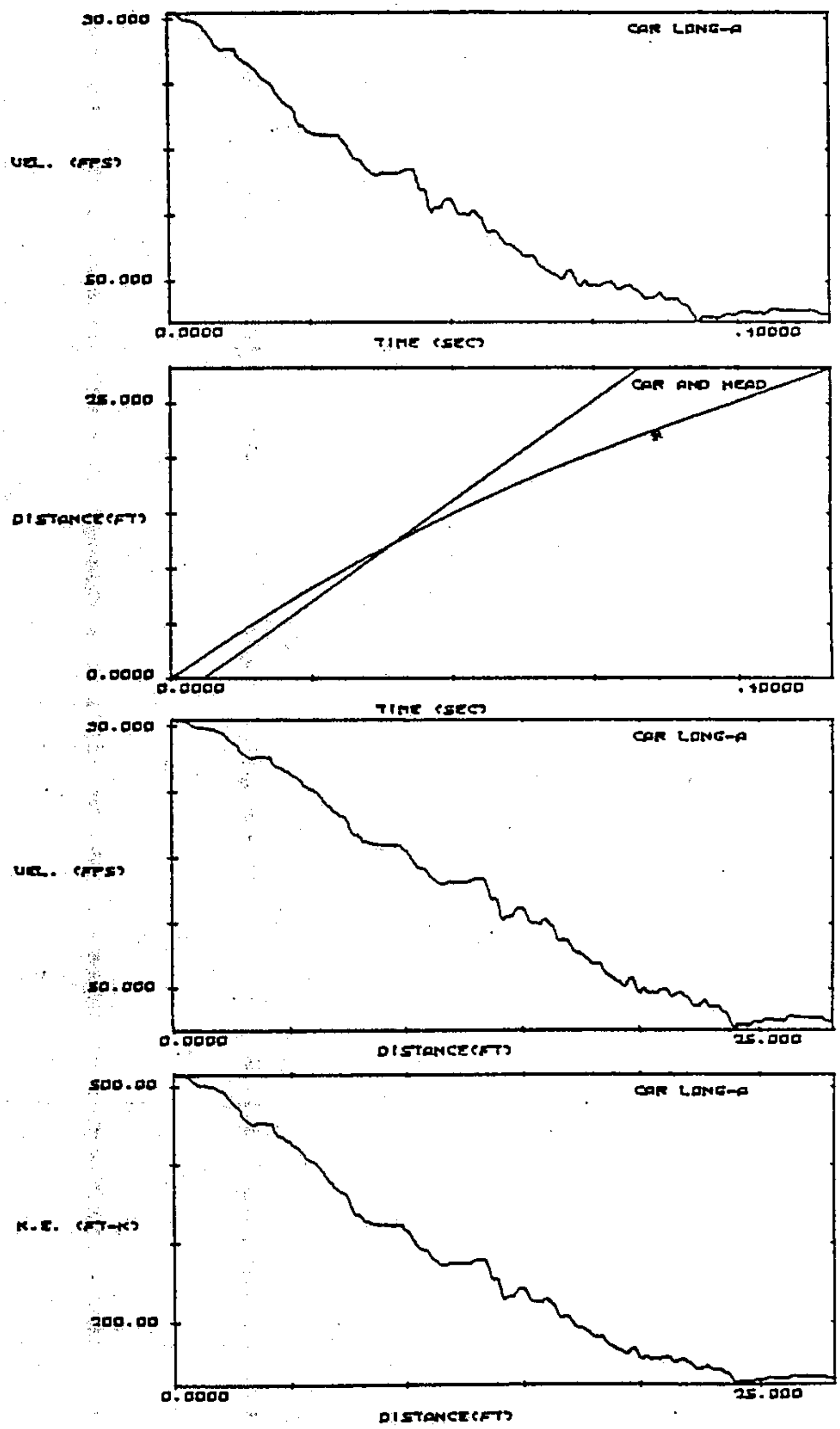


FIGURE C18. TEST 443 - VEHICLE LONGITUDINAL VELOCITY AND DISPLACEMENT VS. TIME

TEST NUMBER

443.00

MOVABLE

MEDIAN

BARRIER

NOV. 18 1987

CAR IMPACT

VELOCITY

(FPS)-

86.971

AT CAR

DISTANCE(FT)

11.957

OCCUPANT

IMPACT

OCCURS

OCCUPANT

IMPACT

VELOCITY

(FPS)-

26.983

OCCURS AT

.16050

SEC. AFTER

CAR IMPACT

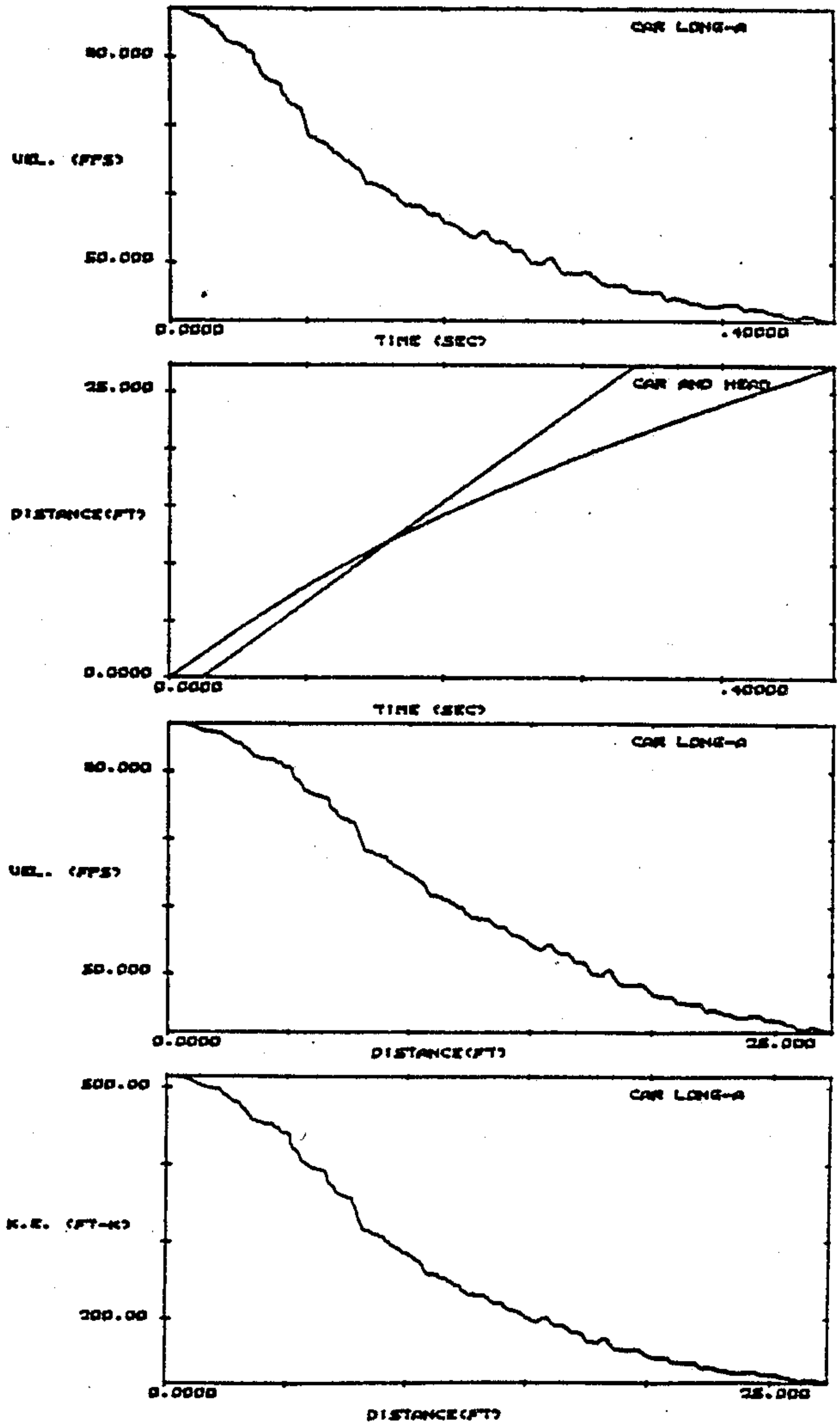


FIGURE C19. TEST 443 - VEHICLE LONGITUDINAL ACCELERATION, VELOCITY AND DISPLACEMENT VS. TIME (PACDAS DATA)

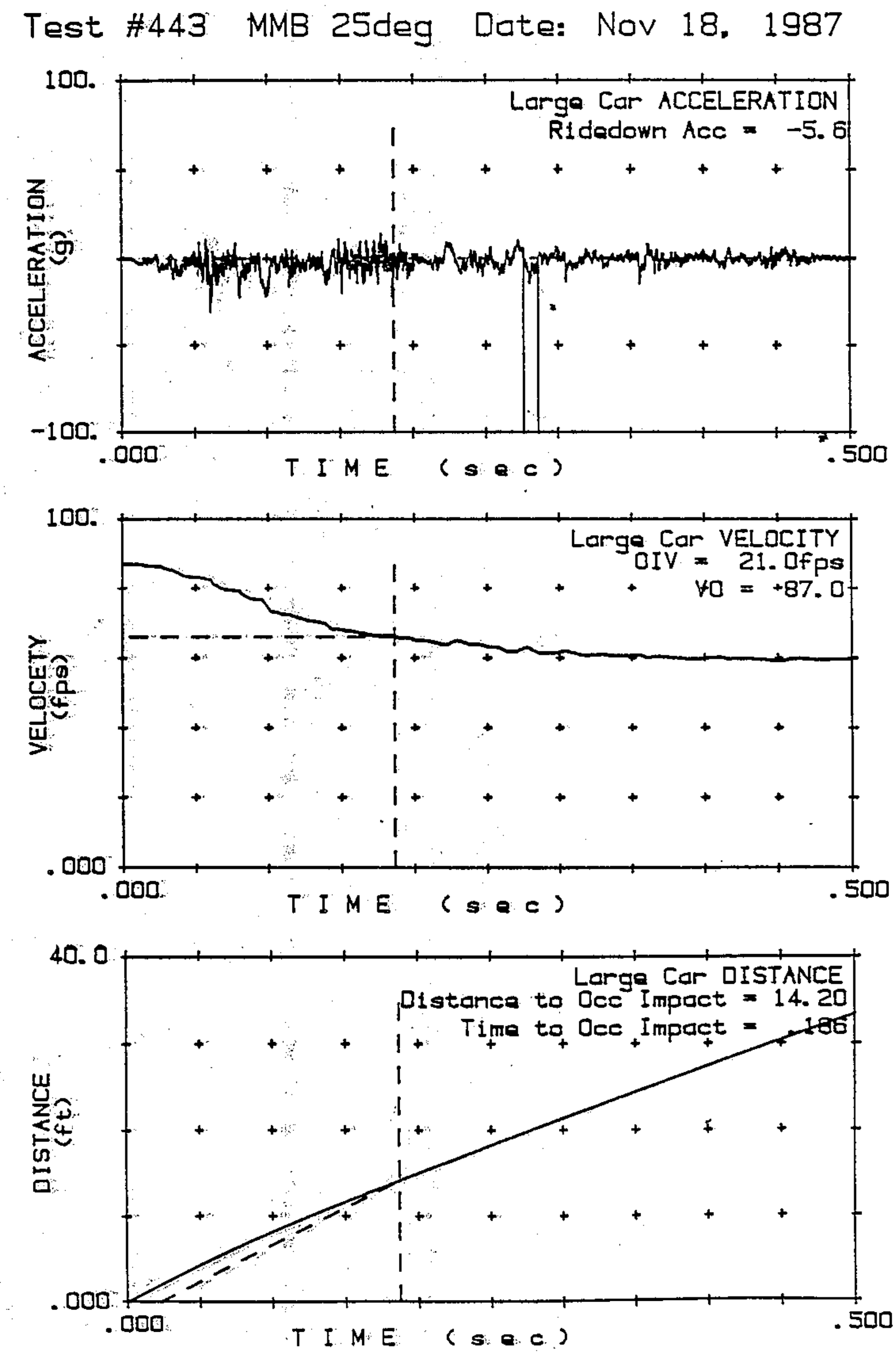


FIGURE C20. TEST 444 - VEHICLE LONGITUDINAL VELOCITY AND DISPLACEMENT VS. TIME

TEST NUMBER
444.00
MOVABLE
MEDIAN
BARRIER

DEC. 18 1987

CAR IMPACT
VELOCITY
(FPS)-
92.401

AT CAR
DISTANCE(FT)
17.679
OCCUPANT
IMPACT
OCCURS

OCCUPANT
IMPACT
VELOCITY
(FPS)-
15.098
OCCURS AT
.21300
SEC. AFTER
CAR IMPACT

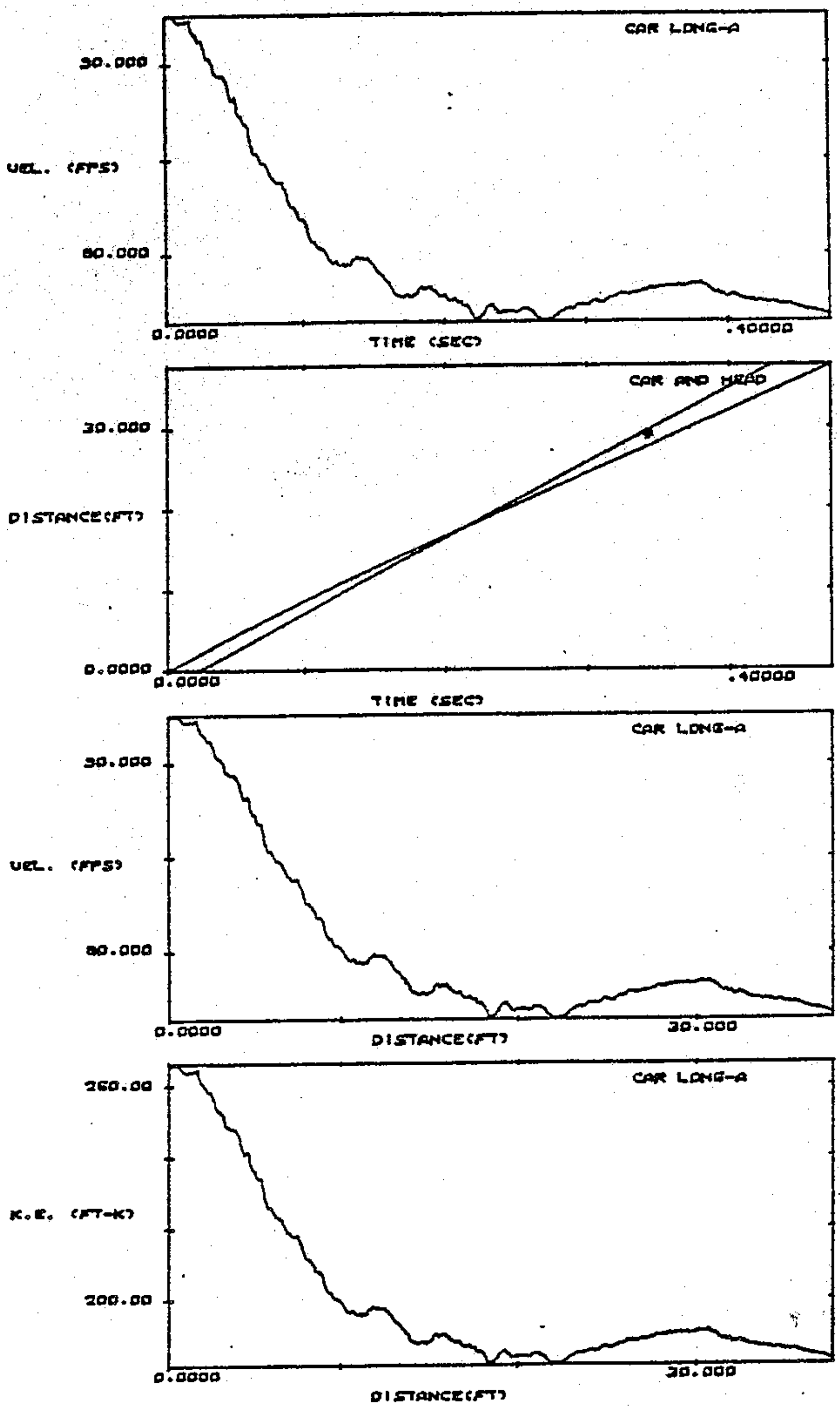


FIGURE C21. TEST 445 - VEHICLE LONGITUDINAL VELOCITY AND DISPLACEMENT VS. TIME.

TEST NUMBER
445.00
MOVABLE
MEDIAN
BARRIER

JAN. 21 1988

CAR IMPACT
VELOCITY
(FPS)-
86.974

AT CAR
DISTANCE(FT)
19.354
OCCUPANT
IMPACT
OCCURS

OCCUPANT
IMPACT
VELOCITY
(FPS)-
14.291
OCCURS AT
.24550
SEC. AFTER
CAR IMPACT

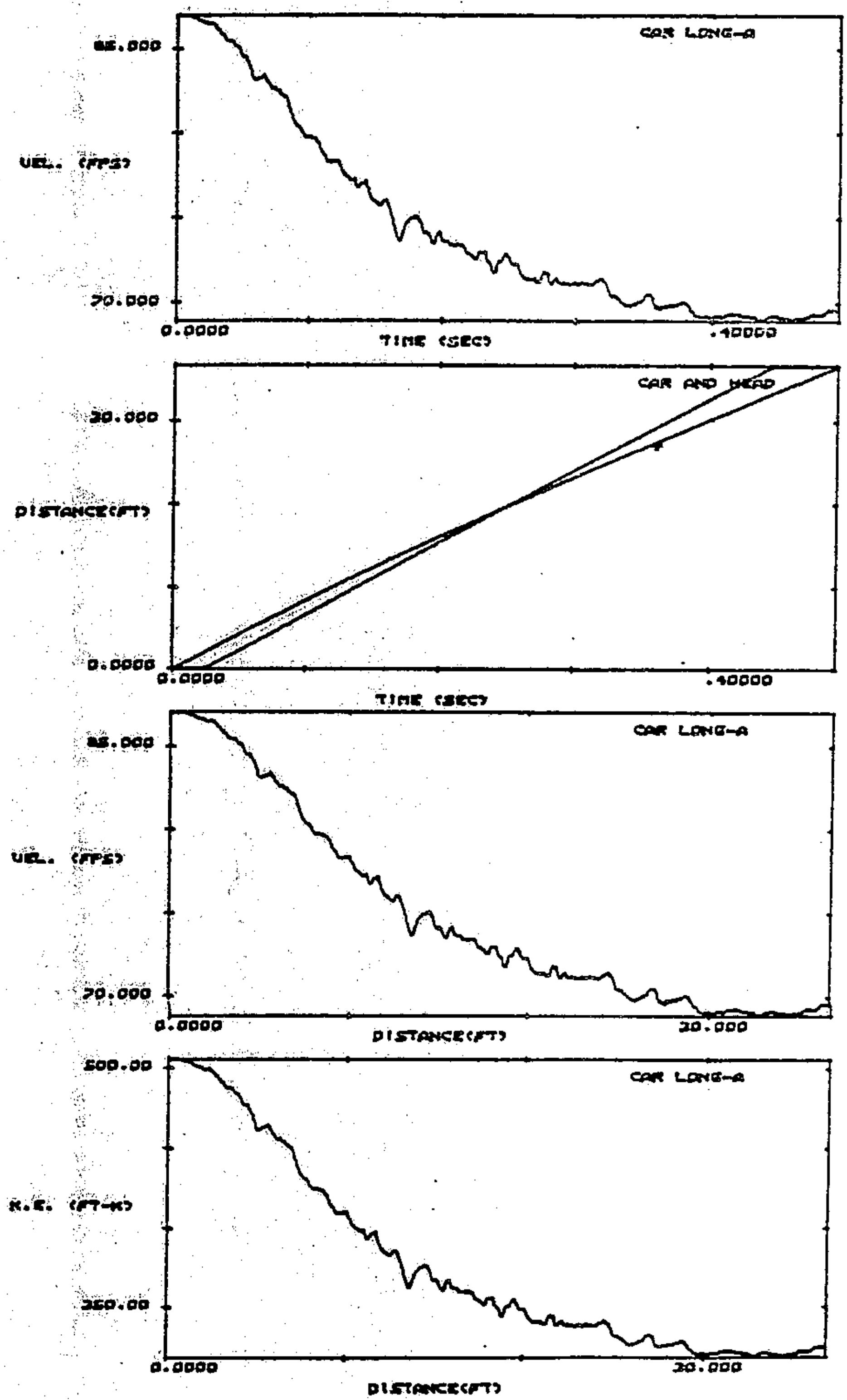


FIGURE C22. TEST 445 - VEHICLE LONGITUDINAL ACCELERATION, VELOCITY AND DISPLACEMENT VS. TIME (PACDAS DATA)

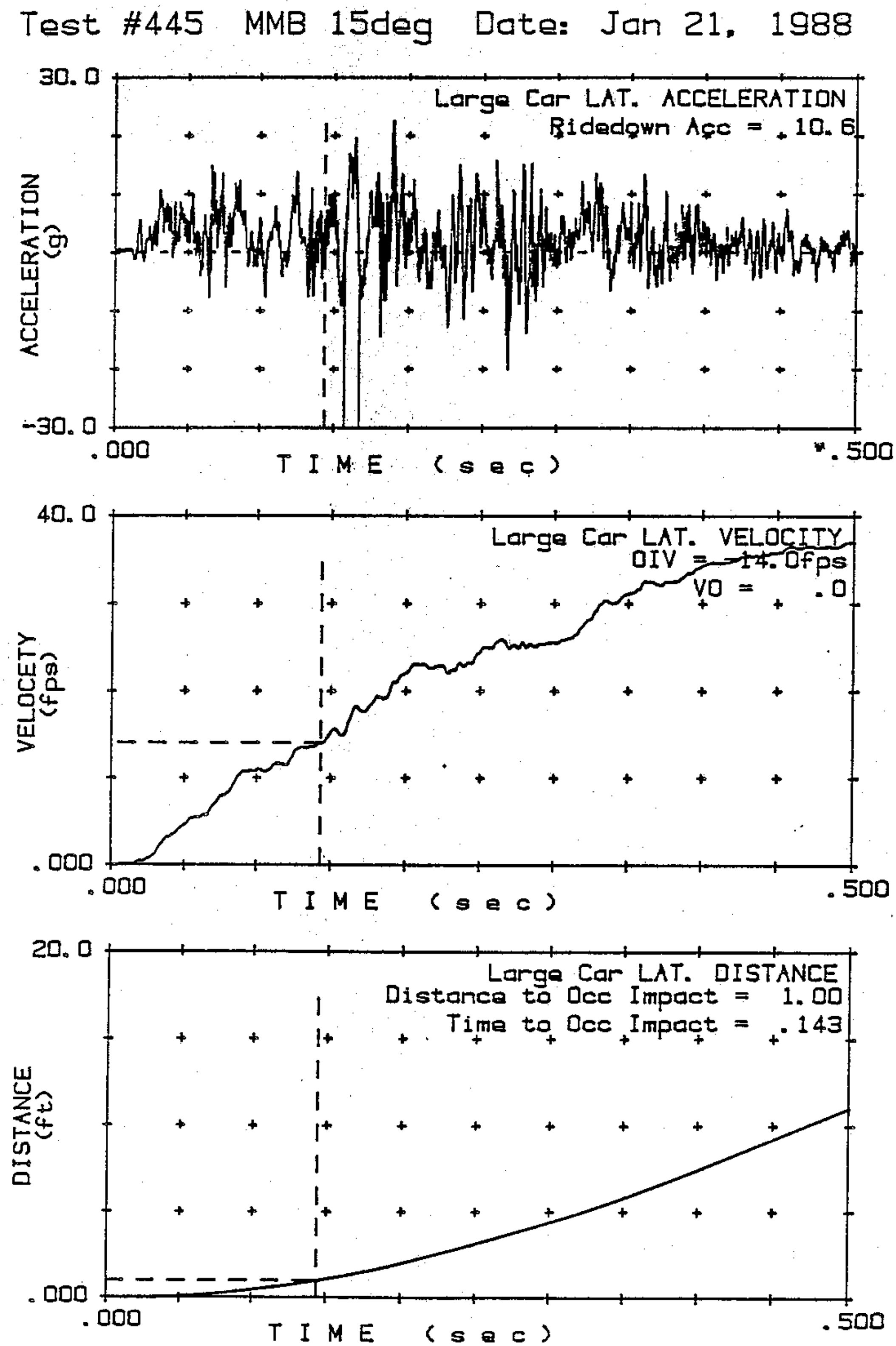


FIGURE C23. TEST 446 - VEHICLE LONGITUDINAL VELOCITY AND DISPLACEMENT VS. TIME

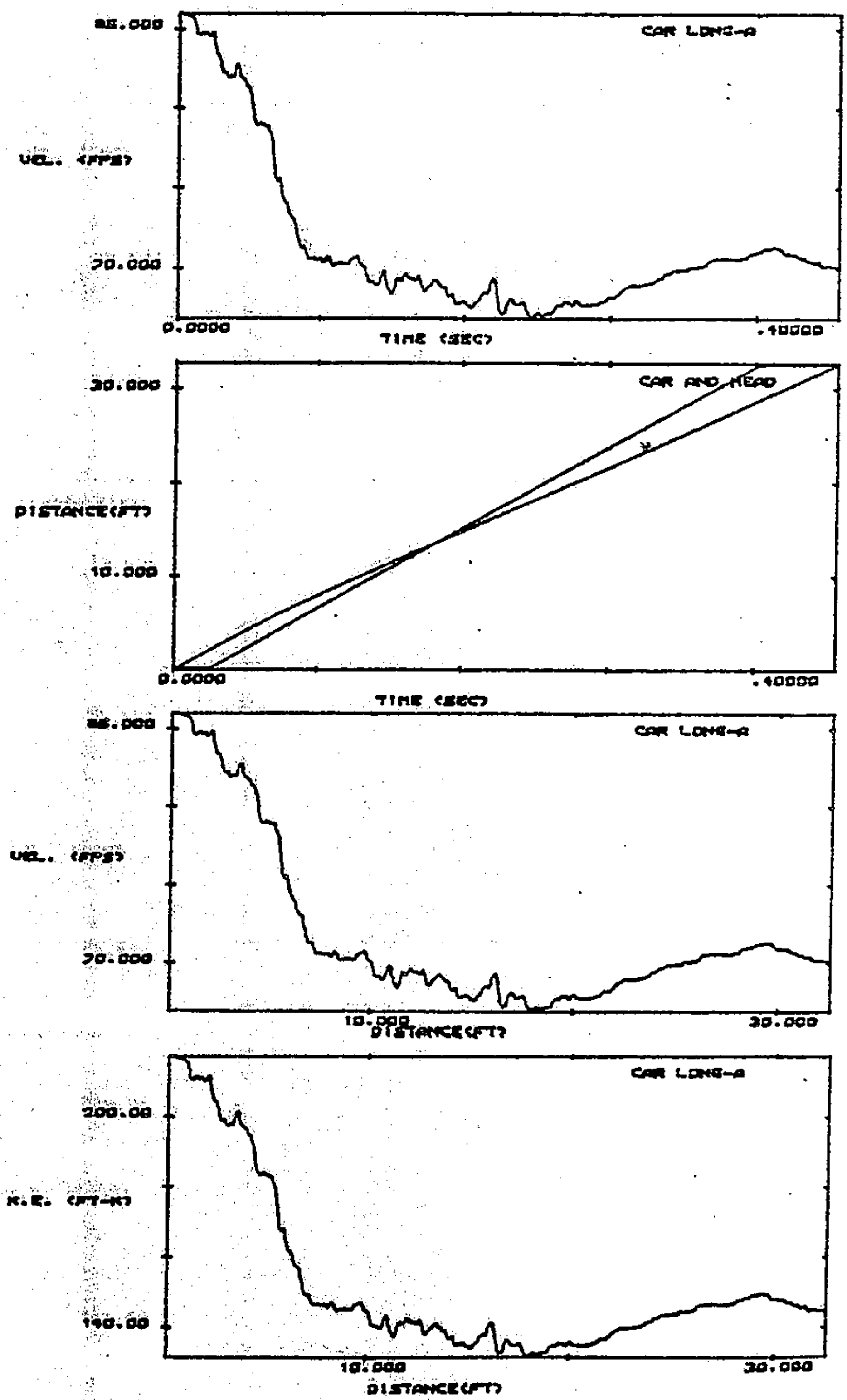
TEST NUMBER
446.00
MOVABLE
MEDIAN
BARRIER

MARCH 9 1988

CAR IMPACT
VELOCITY
(FPS)-
85.944

AT CAR
DISTANCE(FT)
13.599
OCCUPANT
IMPACT
OCCURS

OCCUPANT
IMPACT
VELOCITY
(FPS)-
16.913
OCCURS AT
.18150
SEC. AFTER
CAR IMPACT



Figures D1 through D5 show the complete test barrier plans. Barrier Systems, Inc. prepared all drawings. The plans are for the barriers tested in tests 443 through 446.

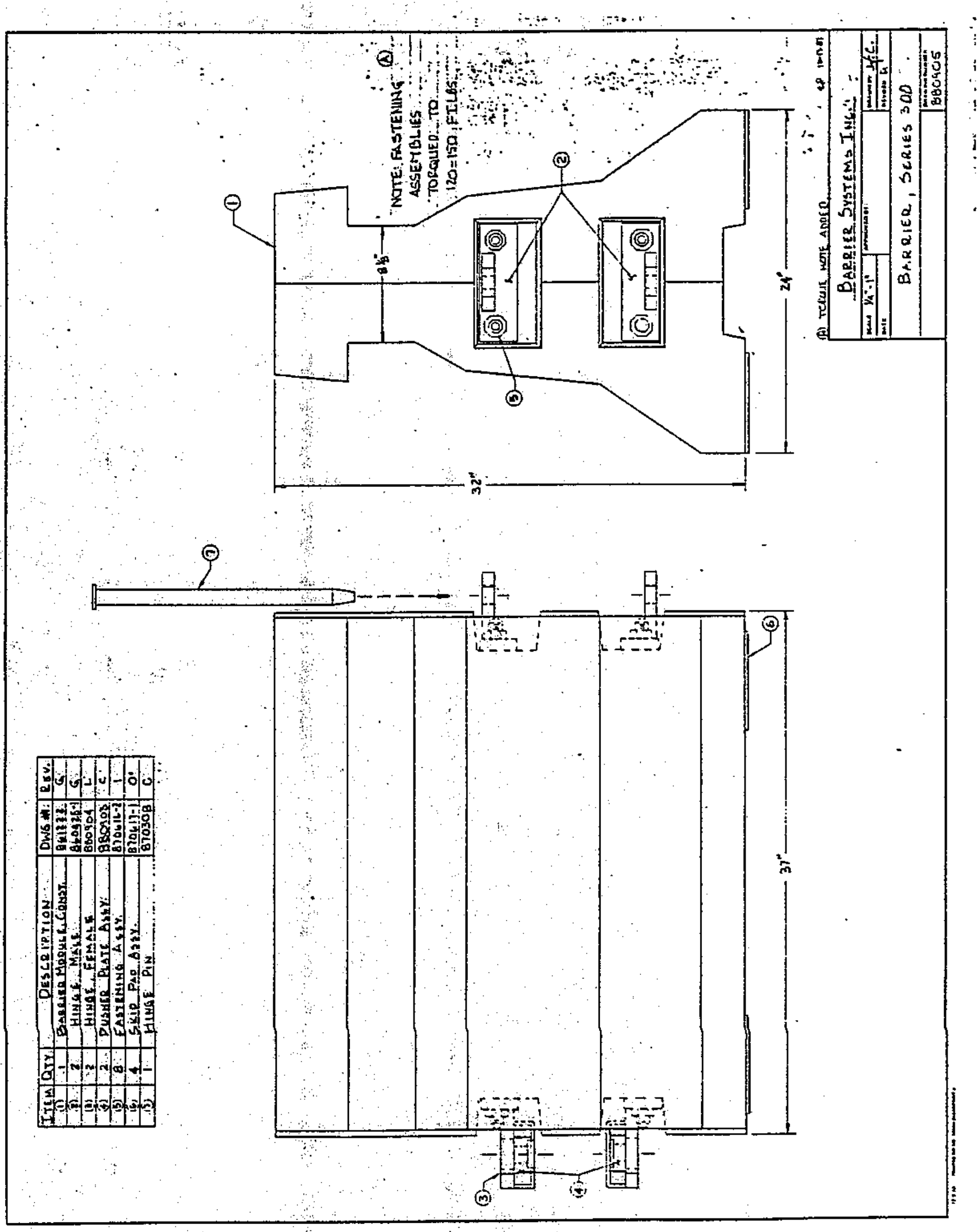

NOTE: FASTENING ASSEMBLIES TORQUED TO 120-150 FT-LBS
BARRIER SYSTEMS INC.
BARRIER, SERIES 300
32"
24"
37"

FIGURE D1

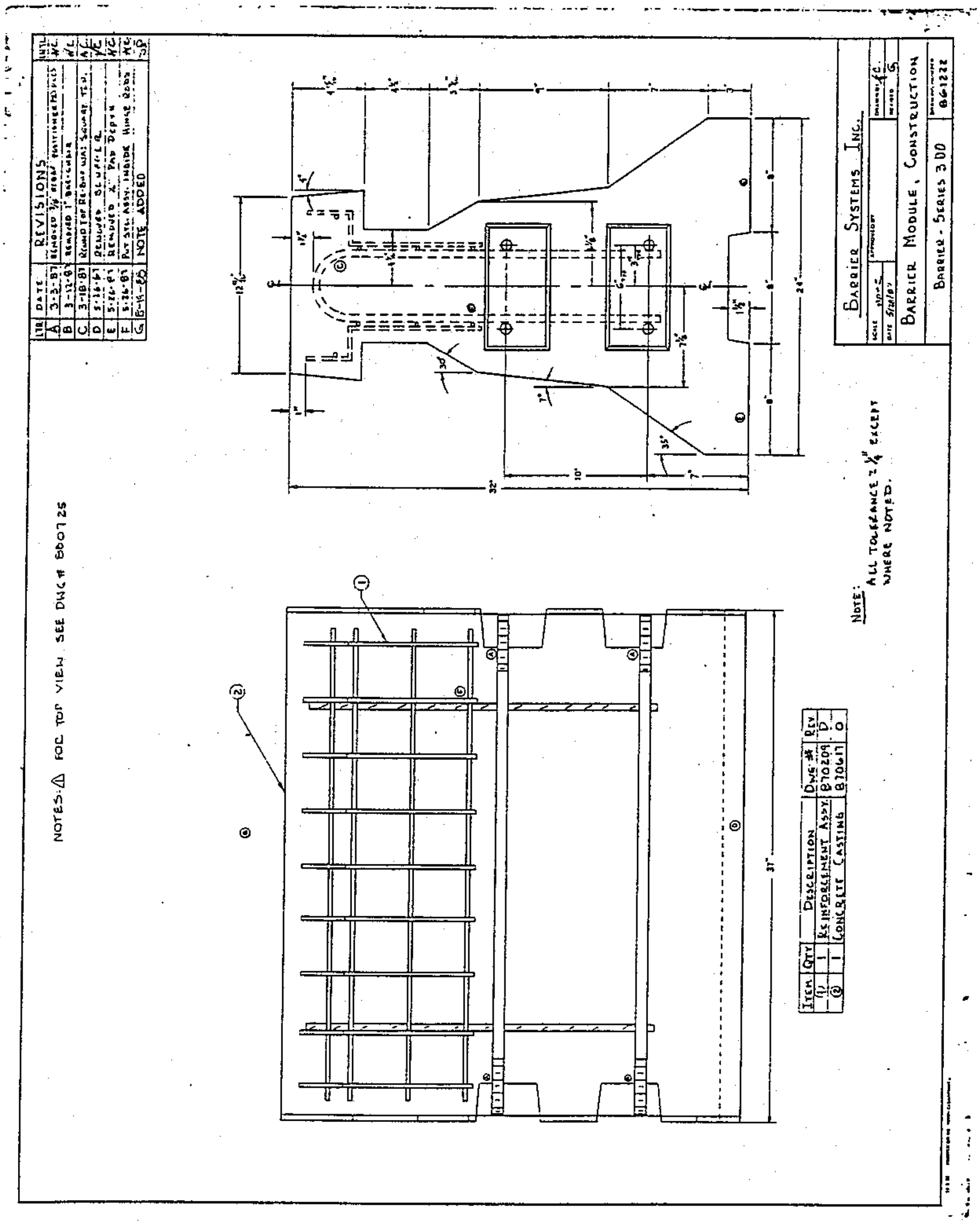

BARRIER SYSTEMS INC.
BARRIER MODULE, CONSTRUCTION
BARRIER - SERIES 3DD
REVISIONS
NOTE: ALL TOLERANCE ± 1/4" EXCEPT WHERE NOTED.

FIGURE D2

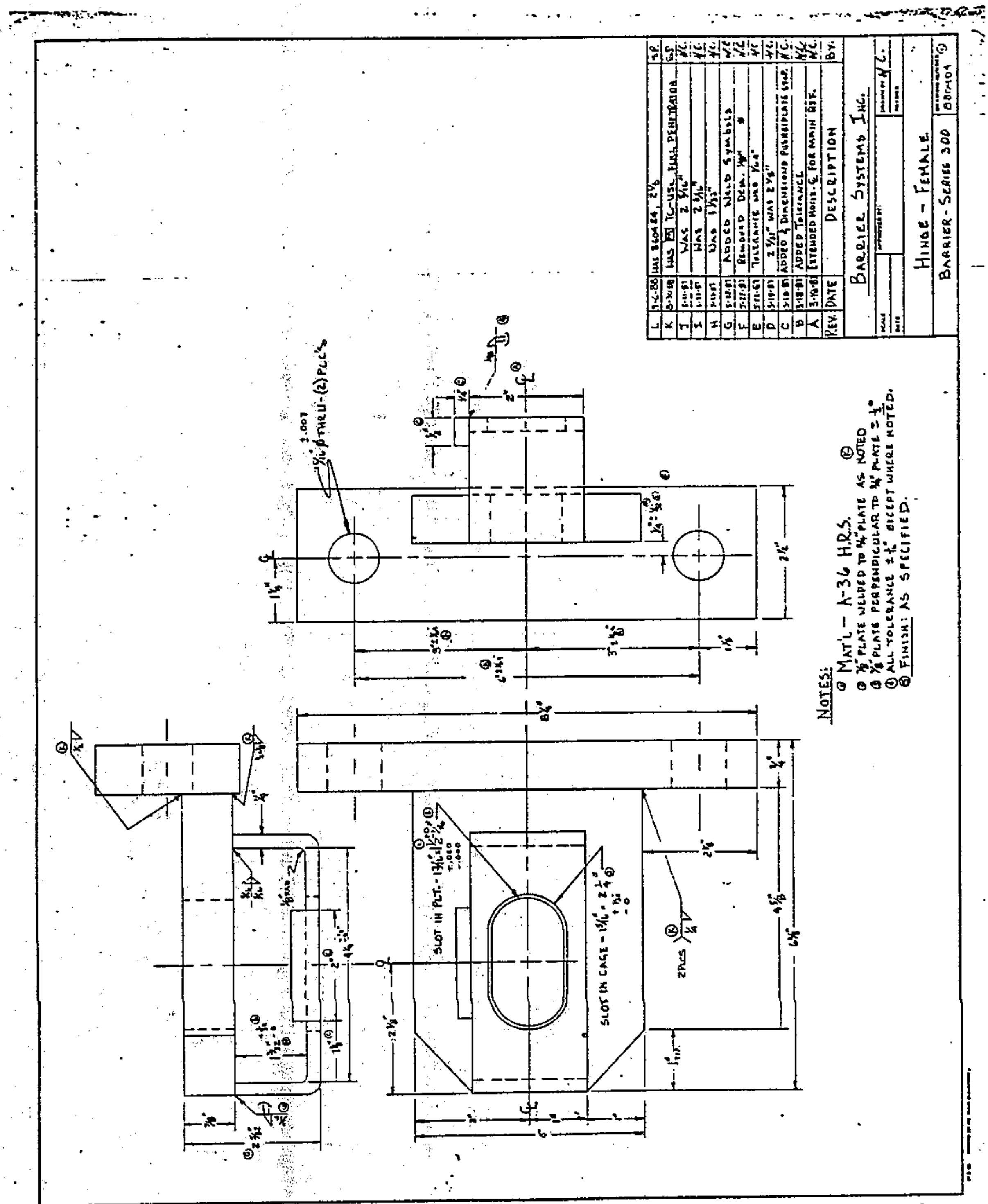


FIGURE D3

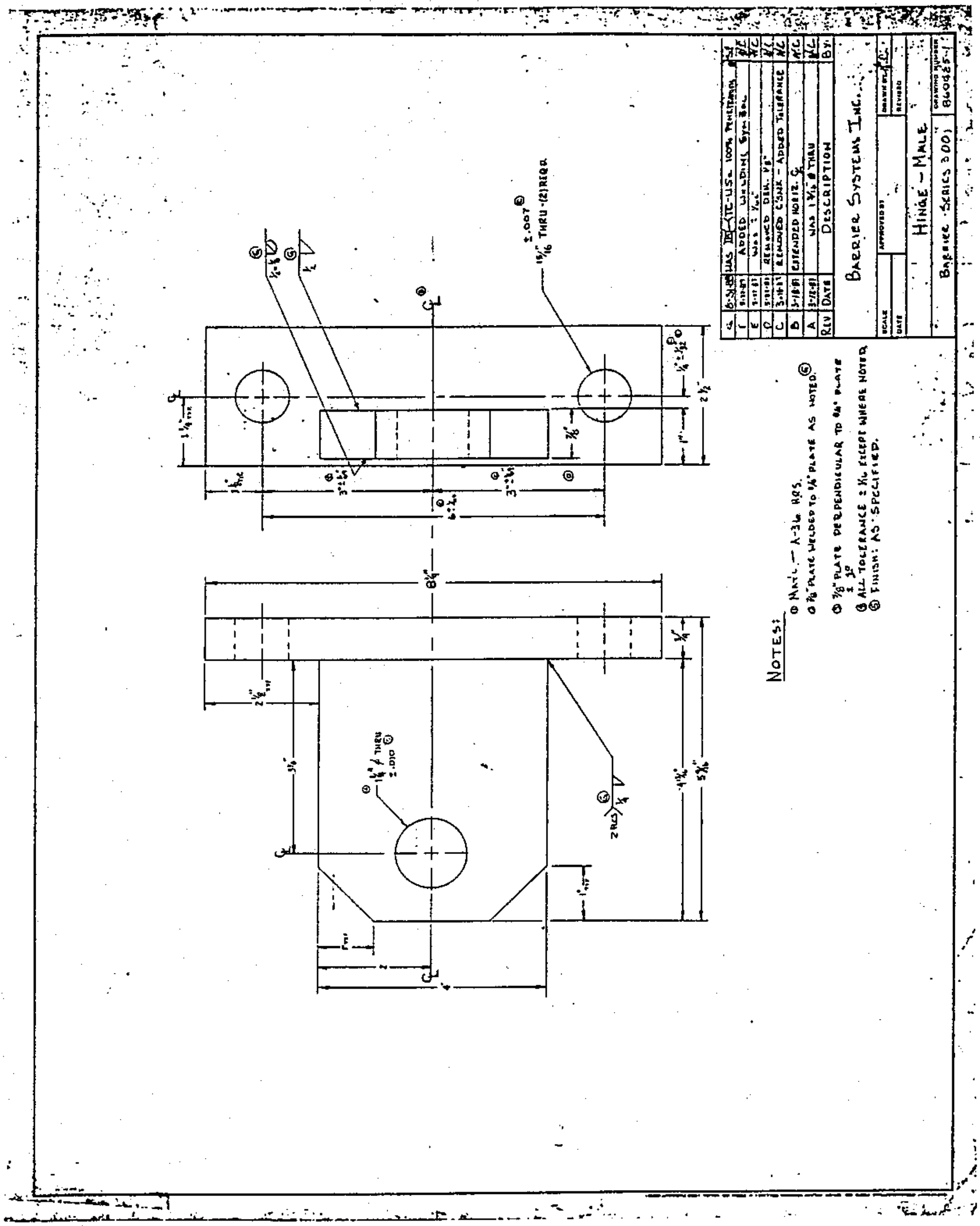


FIGURE D4

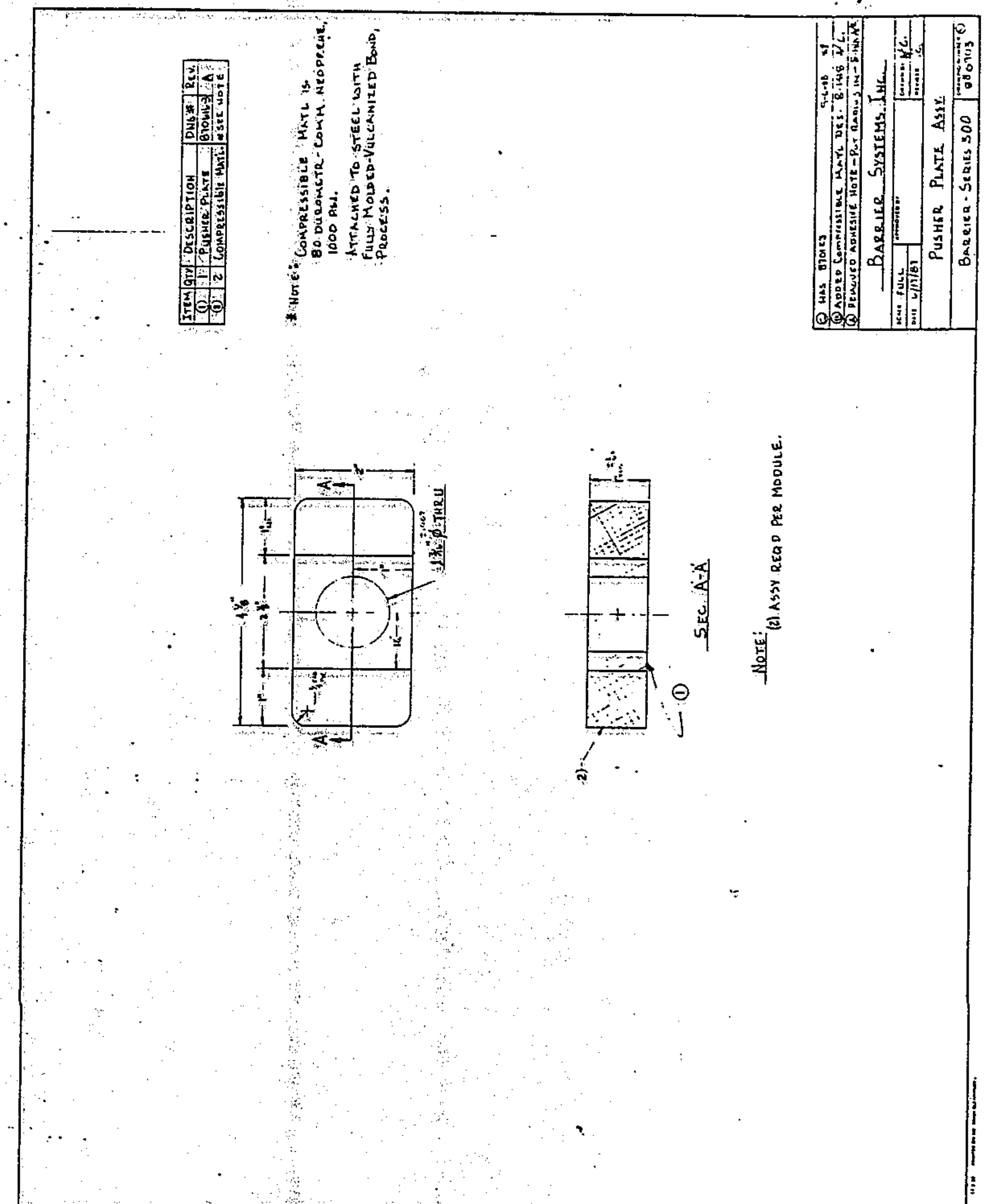

SEC. A-A
NOTE: (2) ASSY REQ'D PER MODULE.
BARRIER SYSTEMS, INC.
PUSHER PLATE ASSY.
BARRIER - SERIES 500

FIGURE D5

Statistical Analysis of Test Data for Two Movable Concrete Barrier Designs: The Quickchange Series 200 Construction Barrier and the Quickchange Series 300 Median Barrier.

There are two sets of crash test data available for movable concrete barriers; the series of tests reported in this report, and the series of tests reported in "Crash Test Evaluation of a Movable Concrete Construction Barrier" (6). The two barriers tested are very similar in design, the only difference is in the hinge detail.

The 12 tests conducted by Barrier Systems Inc. (BSI) and reported by Nordlin were on the BSI Series 200 Construction Barrier. The 4 tests conducted by Caltrans (CT) and reported in this report were on the BSI Series 300 Median Barrier. The hinge detail varies in the longitudinal clearance of the hinge slot; the series 200 has a 1-inch (0.025 m) clearance, the series 300 has a 3/8-inch (0.01 m) clearance.

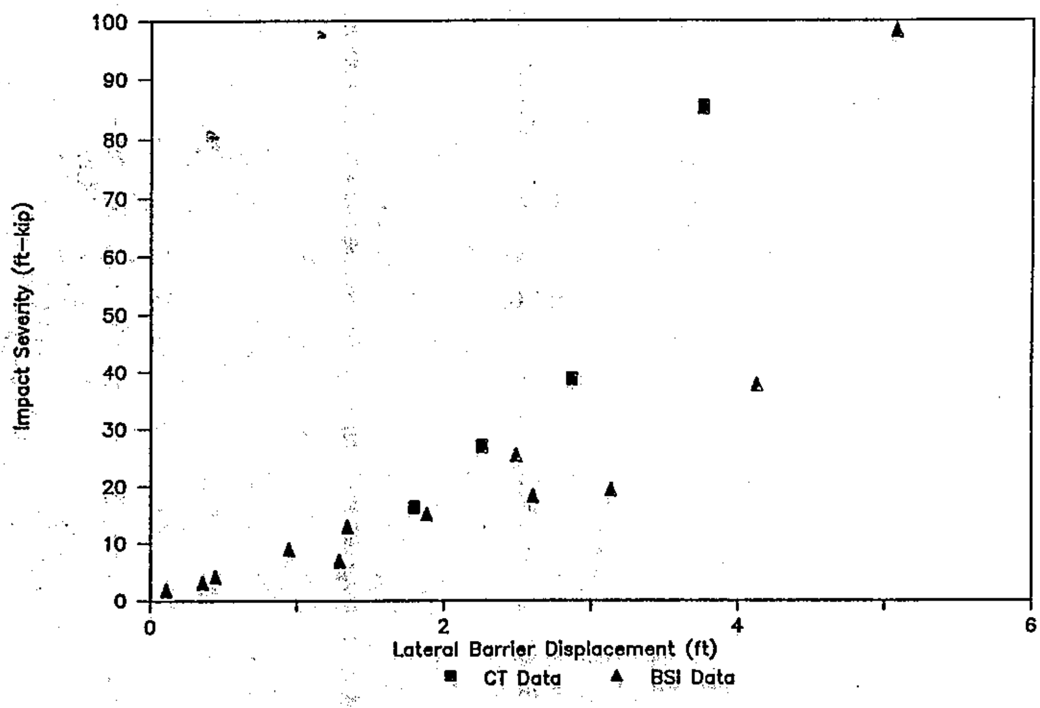
There were three steps in this statistical analysis. First was to find a simple curve to fit each of the data sets. Second, to compare the two curves for differences. And third, to find a more complex curve that better represents the data sets.

All curves were fit by least squares regression. Impact Severity ($IS = 1/2MV^2Sin\theta$) was used as the dependent variable where possible, because that observation is more highly subject to error of measurement than the maximum lateral displacement (D). Sources of error in measuring IS are inaccuracies in measuring impact angle, velocity and vehicle weight. These can each deviate from the true value by a few percent causing a combined error in the calculated IS of 10% or more. Measuring D can be off by 0.01 to 0.02-ft (0.003 to 0.006 m) which could be an error of 0.5 to 10% depending on the value of D.

The first curve to try to fit to the data is the straight line, $y = Ax + B$. This yielded a reasonable correlation $r = 0.957$ and 0.853 for the CT and BSI data respectively. (All values of r reported are corrected for sample size.) Although this is a significant correlation, examination of the residuals showed a substantial curvature in both sets of data (Figure E1). The pattern of the data points suggests a logarithmic relation between D and IS. A regression of the form in $y = A\ln x + B$ yields a better correlation than the linear form above; $r = 0.993$ and 0.949 for CT and BSI data respectively.

FIGURE E1

Barrier Test Data



These regression lines are shown in Figures E2 and E3 on linear axes and log-linear axes, respectively; also shown are the 90% confidence limits for the regressions.

Given that there is a physical difference between the two tested barriers, and that difference is designed to decrease the lateral movement of the series 300 over that of the series 200, there should be a difference in the regression lines that describe the behavior of the two barriers. To determine if there is a difference in the two data sets, a test for parallel slopes of the transformed lines was performed using the Students t statistic. (A paired t-test was considered, but there were no data that could be paired satisfactorily. Also a paired t-test would ignore a substantial amount of available data.).

The test uses the following statistics:

β_O, β_C; estimate of slope for each data set.

$S^2{}_{X_O}, S^2{}_{X_C} = \sum_{i=1}^{n}(X_i - \overline{X})^2$; sum of squares, variance

$SSE_O, SSE_C = \sum_{i=1}^{n}(Y_i - \overline{Y})^2$; sum of squares, residuals

n_O, n_C; number of observations

$S_{pooled} = \left(\frac{SSE_o+SSE_c}{n_o+n_c-4}\right)^{1/2}$; estimate of standard deviation of population

$H_o : \beta_o = \beta_c \qquad H_1 : \beta_o \neq \beta_c$

$$t = \frac{\hat{\beta}_0 - \hat{\beta}_c}{S_{pooled}\sqrt{\frac{1}{S^2_{x_0}} - \frac{1}{S^2_{x_c}}}}$$

calculated t must be greater than the tabulated value of t to reject H_O

Evaluating the above equations using $n_O = 4$ (CTdata) and $n_C = 12$ (BSI data) the calculated value of t is 0.655, the critical value of t at the 90% confidence limit is 1.782 so H_O cannot be rejected. These statistics show that there is not a significant difference in the slopes of the lines fitted through all the available data.

Examination of the plotted data on the log-linear plot shows that the lowest three impact severities fall substantially below a straight line which passes through the remainder of the BSI data points (Figure E3). Examination of the tabulated data for these points (Table G1) shows that they and one other are for impact angles of 7°. These three or four points seem to deviate from the logarithmic model. It can be argued that these four data points should be excluded from the comparison of BSI & CT data on two counts; there are no points in the CT data set in the same range of impact severity or lateral displacement; the impact angle is 7 degrees and all other impact angles are in the range 15 to 25 degrees and very low impact angles may have a different characteristic behavior.

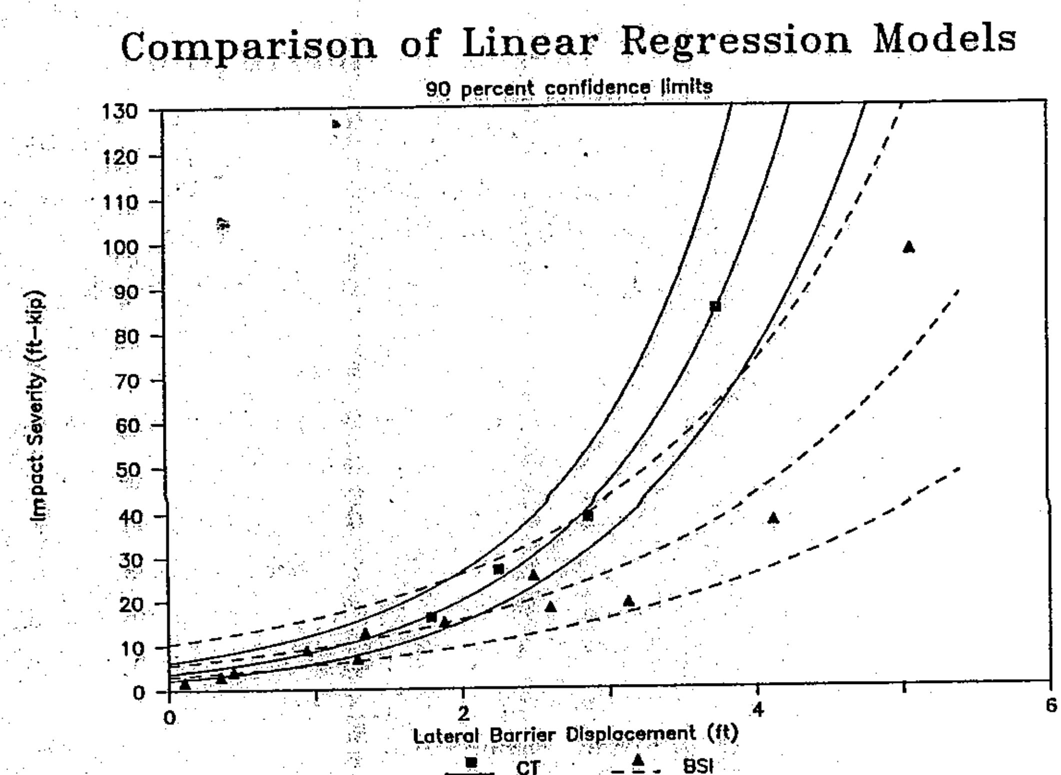
Calculated t-statistic values:

Table E1

n_c	t_{calc}	$t_{critical}$ @ 90%
12	0.655	1.782
8	1.849	1.860

Note that the calculated t-statistic approaches the critical acceptance value when the seven degree angle impacts are removed from the data set (Table E1). This analysis shows that when similar impact conditions exist, there is not a statistically significant difference in the performance of the two barrier systems tested at the ninety percent level. However, if a slightly lower level of significance is accepted, say 80% or 85% then a significant difference exists.

FIGURE E2



Statistical Analysis of Test Data for Two Movable Concrete Barrier Designs: The Quickchange Series 200 Construction Barrier and the Quickchange Series 300 Median Barrier.

FIGURE E3

Comparison of Linear Regression Models

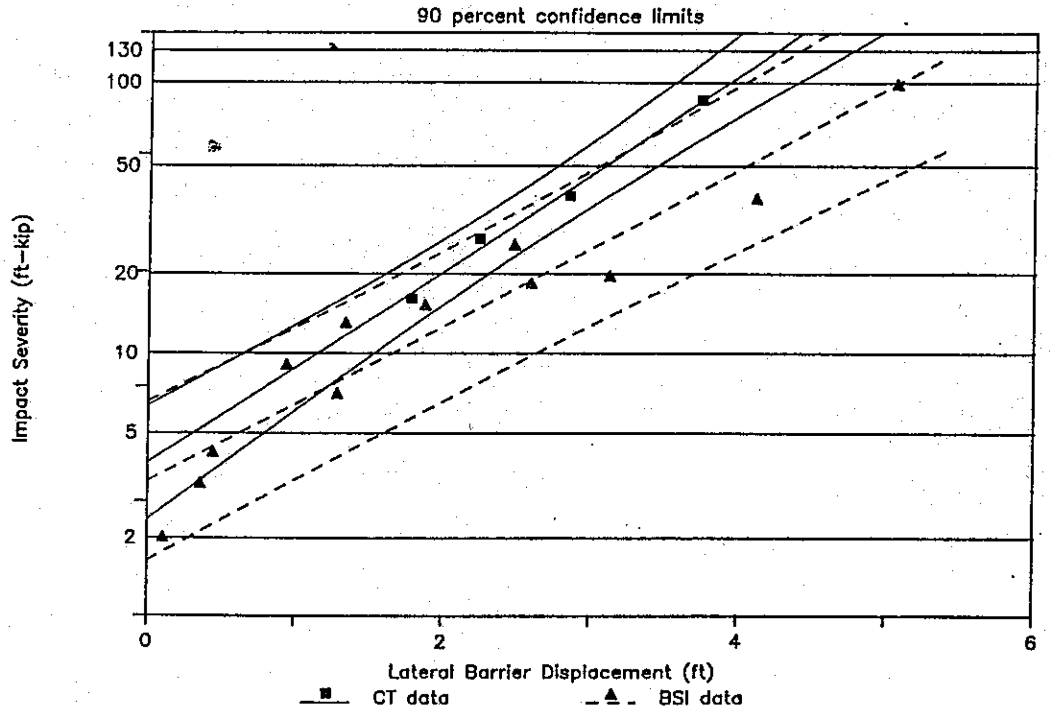
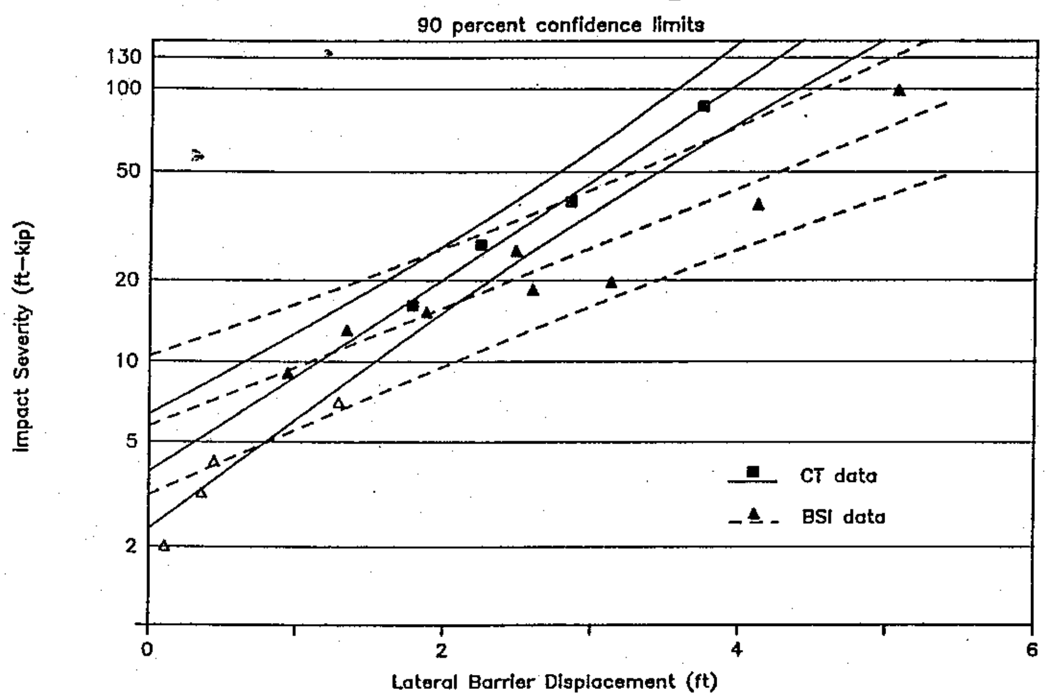


FIGURE E4

Comparison of Linear Regression Models



When examining the BSI data on a log-linear plot (Figure E4) there is an apparent bend in the data near D = 1 ft (0.3 m). This would suggest that a straight line might not be appropriate to best describe the data over its full range. Also, it would not be unreasonable to assume that an equation to describe the lateral displacement vs impact severity for each of the barrier systems would take the same functional form.

Another important consideration is the actual mechanism by which lateral deflection occurs. The system is a series of rigid (nonelastic) elements connected by frictionless hinges with a longitudinal gap. Upon impact the barrier "stretches" by eliminating the gap in the hinge, thus allowing the barrier to assume a non-straight alignment. A larger impact induces more "stretch", in allowing more lateral deflection. The system tested by BSI has larger gaps, so more stretch is allowed for each barrier segment that is added to the mass being moved. For very small impacts, less than the total gap for even one segment is required to allow enough "stretch" for the induced lateral displacement. Hence, for very small impact severities, one might expect that the performance of the two barriers would be identical. (Unfortunately no data for the series 300 barrier is available to confirm this.)

In order to find an equation to predict barrier performance, a computer program called "CURVEFIT" was used (12). CURVEFIT performs a least squares fit for 25 different functional forms. There were two functions which fit the BSI data best, as determined by r^2. They are the Hoerl (equation 1) and Gamma (equation 2) functions;

$$IS = A \cdot B^{D} \cdot D^{C} \qquad (1)$$

and $$IS = A\left(\frac{D}{B}\right)^{C} \exp\left(\frac{D}{B}\right) \qquad (2)$$ respectively, where

A, B and C are coefficients, D is lateral displacement (feet) and IS is impact severity (ft-kips). Both functions had $r^2 = 0.9446$.

Statistical Analysis of Test Data for Two Movable Concrete Barrier Designs: The Quickchange Series 200 Construction Barrier and the Quickchange Series 300 Median Barrier.

FIGURE E5

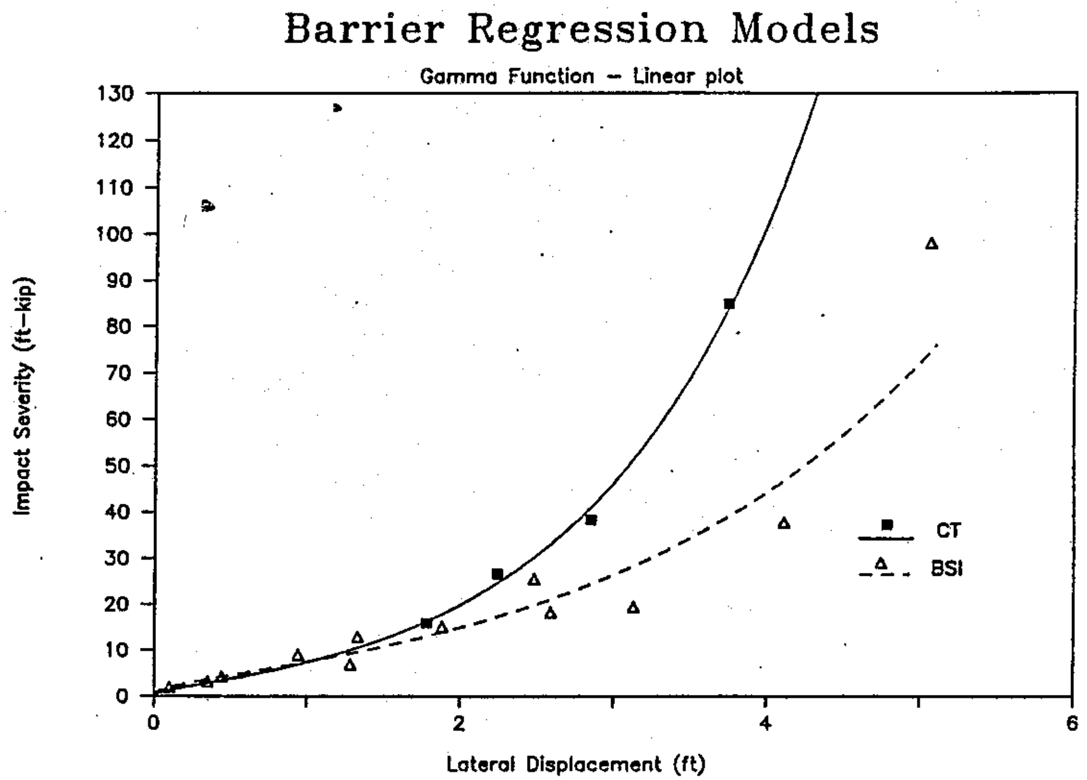
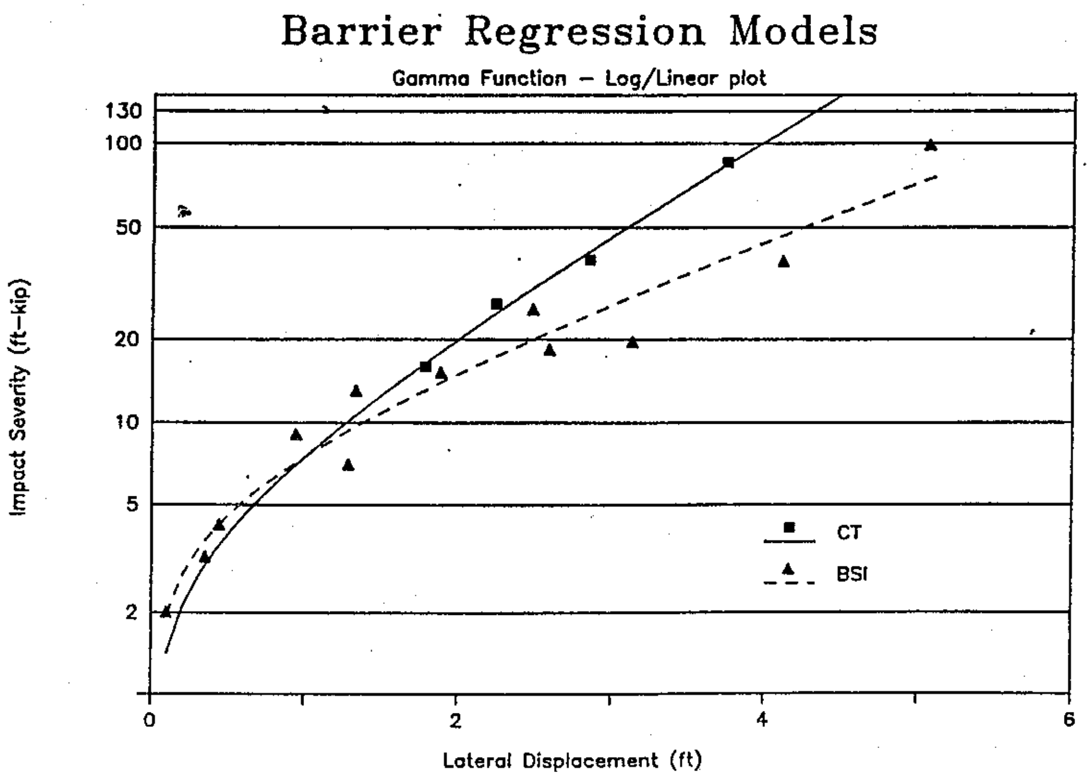


FIGURE E6



The CT data were also fitted to these curve forms, r^2 was 0.9756. Though it was not the best correlation for the four data points, it is a significant correlation at the 95% confidence level.

TABLE E2
Coefficients for Hoerl and Gamma functions

		A	B	C
BSI	Hoerl (1)	5.08	1.48	0.429
	Gamma (2)	7.57	2.54	0.429
CT	Hoerl (1)	3.91	1.92	0.470
	Gamma (2)	4.78	1.53	0.470

In each case, the two functions describe the same line, within one percent. Either function may be used depending on which the user prefers. Figures E5 and E6 show the Gamma function for each data set plotted on linear and log-linear scales respectively. Notice that for values of D less than 1.2 ft (0.37 m) the two barriers are predicted to perform virtually identically; this is consistent with the expectation noted above.

The models discussed so far would be useful for finding an impact severity given a distance moved. (This is due to the fact that least squares of IS has been used.) Simply solving the previously discussed equations for D, to get D as a function of IS, is not possible for the Gamma and Hoerl equations; so a least square about D was performed.

The best fit function is the Modified Hoerl (equation 3).

$$D = A \cdot B^{\left(\frac{1}{IS}\right)}(IS)^C \tag{3}$$

This function also had a significant correlation to the CT data. The Modified Hoerl (3) varies from the Hoerl equation (1) in the exponent of B. Figures E7 and E8 show plots of the Modified Hoerl (3) on linear and linear-log scales.

The equivalence of the Modified Hoerl equation to the Gamma and Hoerl was checked. The Gamma and Hoerl equations were used to calculate impact severities and then the Modified Hoerl equation was used to calculate back to distances. For the range from 0.1 ft to 4 ft (0.03 to 1.2 m) (1 ft-kip to 110 ft-kips = 1.35 to 149 kJ) the final answer was within 0.05 ft (0.015 m), and within 0.1 ft (0.03 m) up to 4.2 ft (1.28 m) (130 ft-kips = 176 kJ).

TABLE E3
Coefficients for Modified Hoerl Function (3)

	A	B	C
BSI	0.872	0.00765	0.417
CT	0.961	0.0125	0.319

To show that the three functions describe essentially the same curves, the set representing the series 300 barrier (based on CT data) are plotted in Figure E9. The three lines can hardly be discerned.

The set of three equations (Hoerl, Gamma and Modified Hoerl) are equivalent within a few percent throughout the range of 0.1 ft to 5.5 ft when used with the coefficients presented here. Any one of the three equations may be used with equal reliability for predicting or assessing the performance of the evaluated barrier systems.

The three equations presented above can be estimated over a certain range using a much simpler equation:

$$\ln(IS) = A + BD \tag{4}$$

FIGURE E7

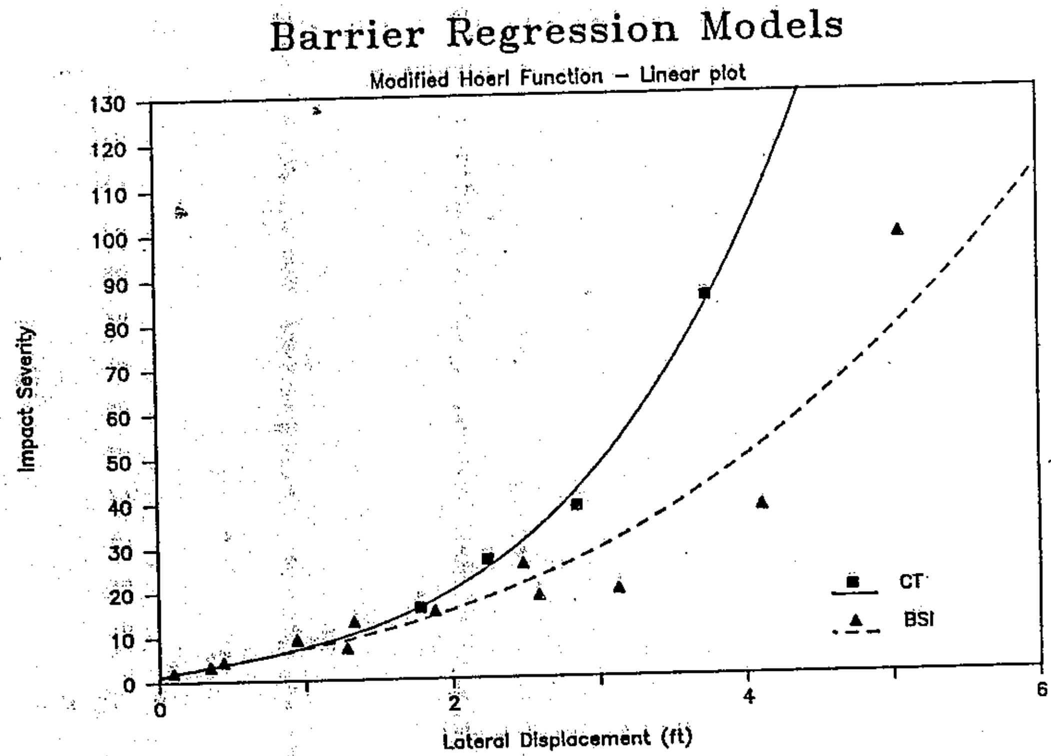


FIGURE E8

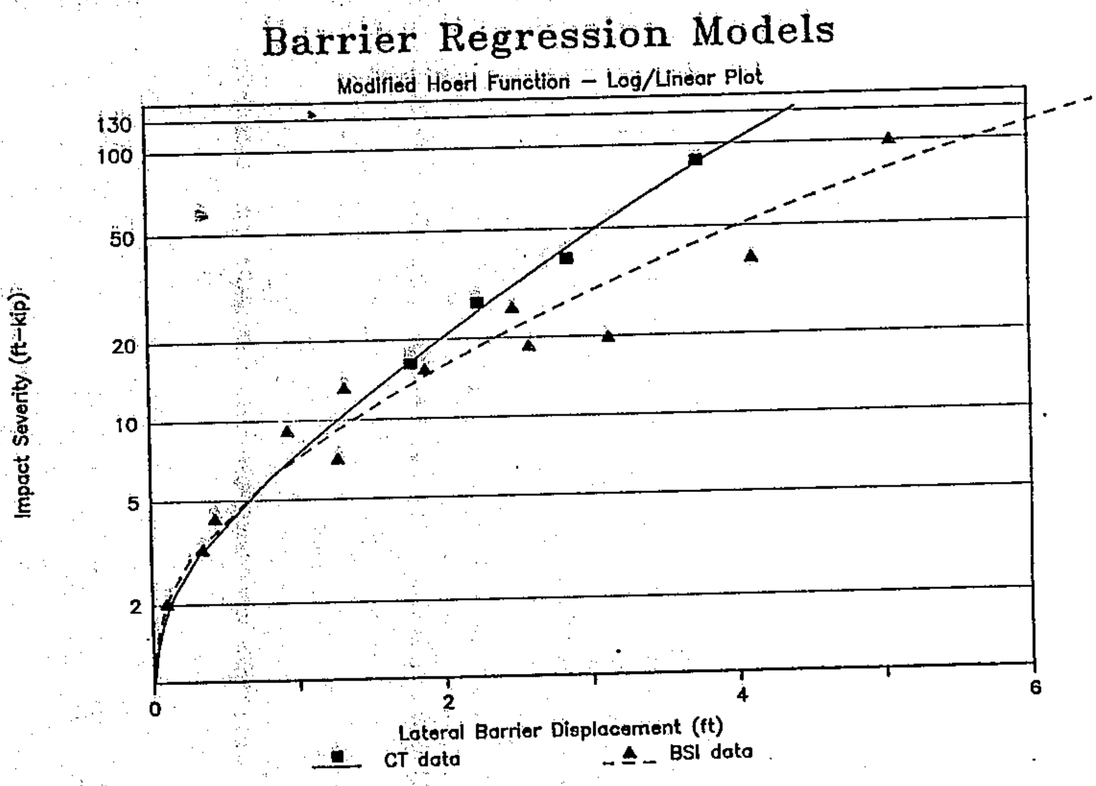
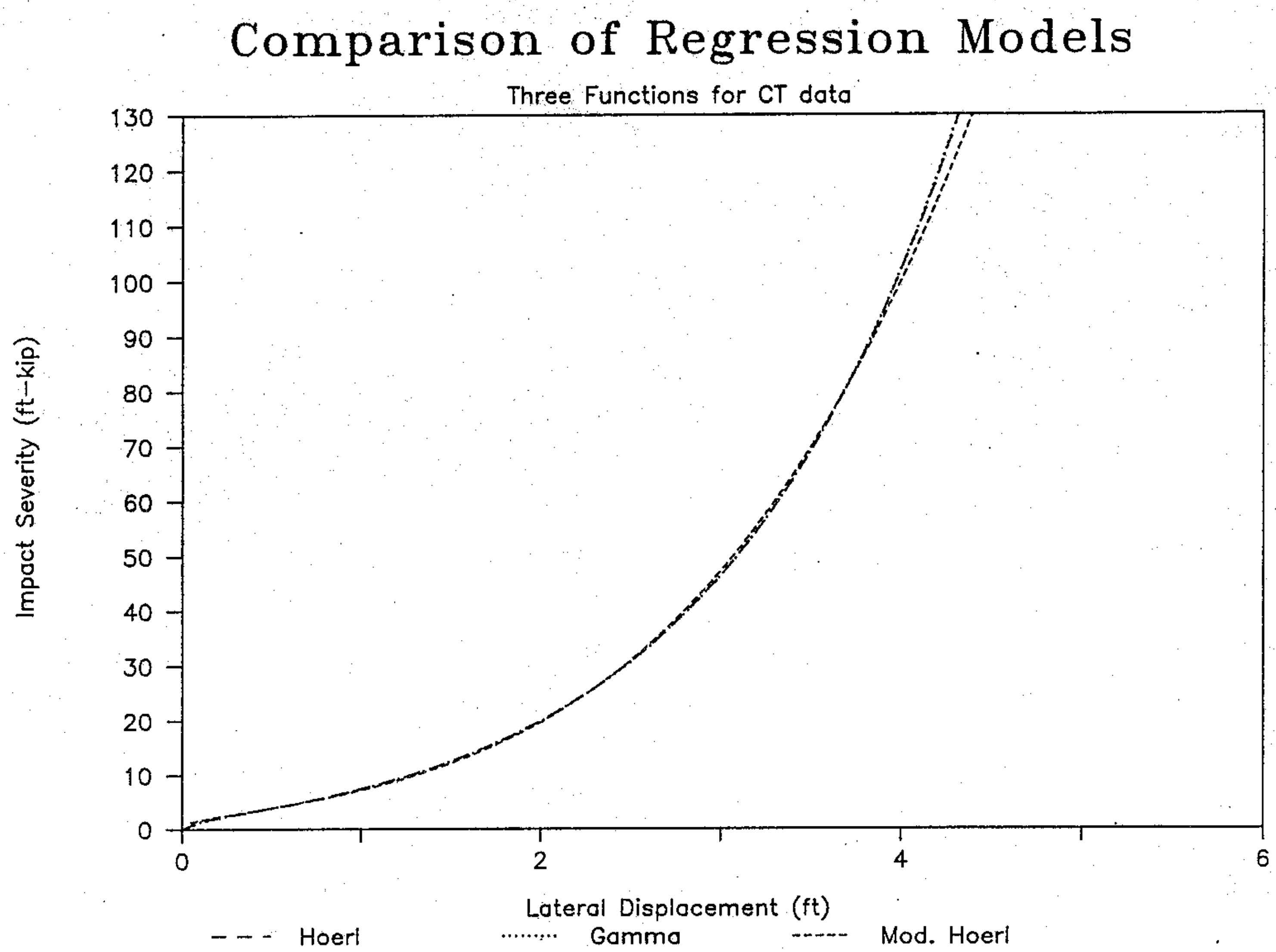


FIGURE E9


Comparison of Regression Models
Three Functions for CT data
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Impact Severity (ft–kip)
0
2
4
6
Lateral Displacement (ft)
Hoerl
Gamma
Mod. Hoerl

Equation 4 can be used for the range of impact severities from 15 to 130 ft-kips (20 to 175 kJ). This equation gives the same answers as those above within a few percentage points for the entire range.

TABLE E4
Coefficients for Logarithmic Equation

	A	B
BSI	1.74	0.507
CT	1.34	0.828

There have been 4 equations presented to estimate the performance of two movable concrete barrier systems. All equations are based on least squares best fit for each form. For their respective applicable ranges none can be called better than any other, since none fit the data exactly. Hence, any one or more than one can be used as an effective model for evaluating the performance of these barrier systems. The more complicated equations have the advantage that they will yield answers for less severe impacts. The simpler logarithmic equation has the advantage that confidence intervals can be calculated, though it is not done here.

The coefficients presented above can be used only when D is in feet and IS is in ft-kips. When using metric units the coefficients in Table E5 are applicable.

TABLE E5
Coefficients for Equations 1, 2, 3 and 4
Using Metric Units

		A	B	C
BSI	1	9.27	8.50	0.470
	2	6.49	0.467	0.470
	3	0.266	0.00263	0.319
	4	1.622	2.74	-
CT	1	11.6	3.55	0.438
	2	10.5	0.789	0.438
	3	0.227	0.00161	0.425
	4	1.347	2.427	-
D is in meters, IS is in kilojoules.				

Various measurements were taken before and after crash tests. Additional measurements to those already presented in the body of the report are included in tables and figures as follows:

- Test vehicles front profiles - Tables and Figures F1 through F6.
- Barrier joint lateral displacement in Tests 441 and 442- Table F7.
- Barrier joint longitudinal displacement in Test 442 - Tables F8.
- Barrier joint location in Tests 443 through 446 - Tables F9 through F12.
- Barrier joint measurements in transfer vehicle demonstration - Table F13
- Displacement of downhill end of the barrier in transfer vehicle demonstration Table F14.
- Plots of survey measurements on car direction of travel and final car location in Tests 443 through 446 (Figures F7 through F10).

TABLE F1

TEST VEHICLE FRONT PROFILE - TEST 441

Car Side	Distance from C/L inches.	Hood Edge, inches (31" Above Ground)		Bumper, inches (20" Above Ground)	
		Before Crash	After Crash	Before Crash	After Crash
Right	39	-	-	17 1/4	18
	36	23 3/4	-	15 3/4	14 1/4
	33	19 3/4	18	15 5/8	14 1/4
	30	21 7/8	20 1/4	15 1/2	14 1/4
	27	21 7/8	20 1/8	15 1/4	14 1/4
	24	21 3/4	20 1/8	15 1/4	14 1/4
	21	21 3/4	20 1/8	12 3/4	11 3/8
	18	19 1/4	20 1/8	15	14
	15	18 7/8	17 5/8	14 5/8	13 3/4
	12	18 1/2	17	14 3/8	13 3/8
	9	18 1/8	16 1/2	14	13 1/8
	6	17 3/4	16	13 1/2	13
	3	17 3/8	15 5/8	13 1/4	12 1/2
C/L	0	17	15 3/8	13	12 3/8
Left	3	17 3/8	15 1/4	13 1/4	12 7/8
	6	17 3/4	15 5/8	13 1/2	15 1/4
	9	18 1/8	16	14	13 3/4
	12	18 1/2	16 3/8	14 3/8	14 1/4
	15	18 7/8	16 3/4	14 5/8	13 3/4
	18	19 1/4	17 1/8	15	15 1/8
	21	21 3/4	17 1/4	12 3/4	12 3/4
	24	21 3/4	19 1/2	15 1/4	16
	27	21 7/8	19 3/4	15 1/4	12 1/4
	30	21 7/8	20 1/8	15 1/2	21 1/4
	33	19 3/4	20 5/8	15 5/8	27
	36	23 3/4	18 5/8	15 3/4	-
	39	-	-	17 1/4	-

FIGURE F1

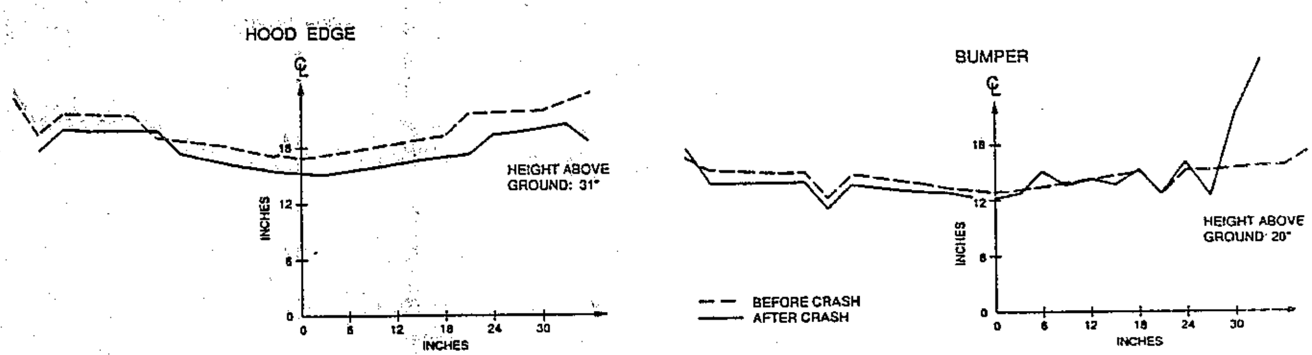


TABLE F2

TEST VEHICLE FRONT PROFILE - TEST 442

Car Side	Distance from C/L Inches.	Bumper, Inches (20" Above Ground)		Hood Edge, inches (31" Above Ground)	
		Before Crash	After Crash	Before Crash	After Crash
Right	39	26 1/4	-	-	-
	36	19 1/4	-	27	-
	33	18 3/4	-	23 3/8	25
	30	18 5/8	46	23 3/8	24
	27	18 5/8	42	23 3/8	22 3/4
	24	18 5/8	41 1/4	23 3/8	22
	21	16	40	23 1/4	21
	18	18 3/8	39 1/2	22 5/8	17
	15	18 1/4	37 1/2	22 1/4	16 1/4
	12	17 7/8	35 3/4	21 15/16	16
	9	17 5/8	33 3/8	21 5/8	15 7/8
	6	17 1/4	32	21 3/16	15 5/8
	3	17	29 3/4	21	15 1/2
C/L	0	16 3/4	28 1/2	20 3/4	15 3/8
Left	3	17	26 1/2	21	15 5/8
	6	17 1/4	25 1/4	21 3/16	16 1/4
	9	17 5/8	23	21 5/8	16 3/4
	12	17 7/8	22 1/4	21 15/16	17 3/8
	15	18 1/4	20 1/2	22 1/4	17 7/8
	18	18 3/8	19	22 5/8	18 1/2
	21	16	17 5/8	23 1/4	19 1/4
	24	18 5/8	15 1/2	23 3/8	19 3/8
	27	18 5/8	14 3/4	23 3/8	19 5/8
	30	18 5/8	14	23 3/8	19 3/4
	33	18 3/4	13 3/4	23 3/8	20
	36	19 1/4	14 1/2	27	21 1/2
	39	26 1/4	-	-	-

FIGURE F2

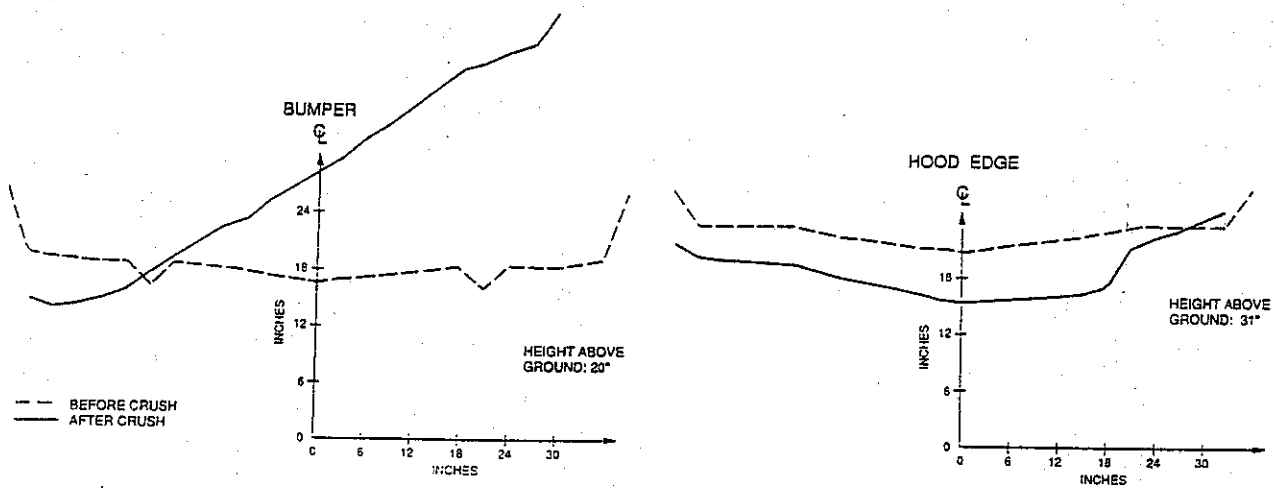


TABLE F3

TEST VEHICLE FRONT PROFILE - TEST 443

Car Side	Distance from C/L Inches.	Bumper, inches (20" Above Ground)		Center of Grill, inches (26" Above Ground)	
		Before Crash	After Crash	Before Crash	After Crash
	36	20 1/2	17 1/2	-	-
	33	15 1/2	17 1/8	20	18 3/4
	30	15	17	20	18 5/8
	27	15	17	20	18 5/8
	24	15	16 7/8	20	18 5/8
	21	14 7/8	16 3/4	20	18 5/8
	18	14 3/4	16 1/4	19 7/8	18 5/8
	15	14 1/4	15 3/4	19 1/2	18 1/4
	12	13 7/8	15 1/4	19	17 3/4
	9	13 1/4	13 1/2	18 1/2	17 1/4
	6	12 3/4	14 1/2	18	16 3/4
	3	12 3/8	14	17 1/2	16 1/4
C/L	0	12	13 3/4	17 1/4	15 3/4
Left	3	12 3/8	14	17 1/2	16 1/4
	6	12 3/4	14 1/2	18	16 3/4
	9	13 1/4	13 1/2	18 1/2	17 1/4
	12	13 7/8	15 1/2	19	17 3/4
	15	14 1/4	16	19 1/2	18 1/4
	18	14 3/4	16 1/4	19 7/8	18 3/4
	21	14 7/8	16 1/4	20	19 1/8
	24	15	16 3/4	20	19 1/4
	27	15	20 1/4	20	19 1/2
	30	15	25 1/2	20	19 7/8
	33	15 1/2	36	20	-
	36	20 1/2	-	-	-

FIGURE F3

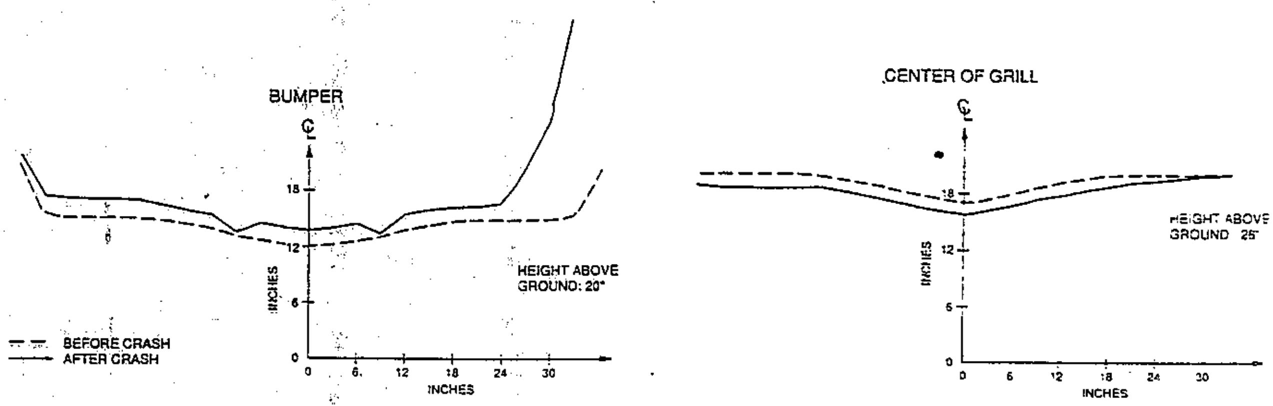


TABLE F4

TEST VEHICLE FRONT PROFILE - TEST 444

Car Side	Distance from C/L inches.	Bumper, inches (18" Above Ground)		Hood Edge Inches (38" Above Ground)	
		Before Crash	After Crash	Before Crash	After Crash
Right	30	14	15 1/4	-	-
	27	14 3/8	14 1/8	18 1/4	18 3/4
	24	14 1/4	14 3/4	18 1/4	18 1/4
	21	14 1/8	14 5/8	18	18
	18	13 1/4	13 3/4	17 1/2	17 5/8
	15	13 1/8	13 3/4	16 1/4	16 1/2
	12	13 1/8	13 3/4	16	16 3/8
	9	13	13 3/4	16	16 3/8
	6	13	13 3/4	15 7/8	16 1/4
	3	13	13 3/4	15 3/4	16 1/4
C/L	0	13	13 3/4	15 3/4	16 1/4
Left	3	13	13 3/4	15 3/4	16 3/8
	6	13	13 3/4	15 7/8	16 1/2
	9	13	13 7/8	16	16 5/8
	12	13 1/8	14	16	16 3/4
	15	13 1/8	14 1/8	16 1/4	17
	18	13 1/4	15 1/8	17 1/2	18
	21	14 1/8	18 1/4	18	18 5/8
	24	14 1/4	21 3/8	18 1/4	21 1/4
	27	14 3/8	32 3/4	18 1/4	-
	30	14	55 1/2	-	-

FIGURE F4

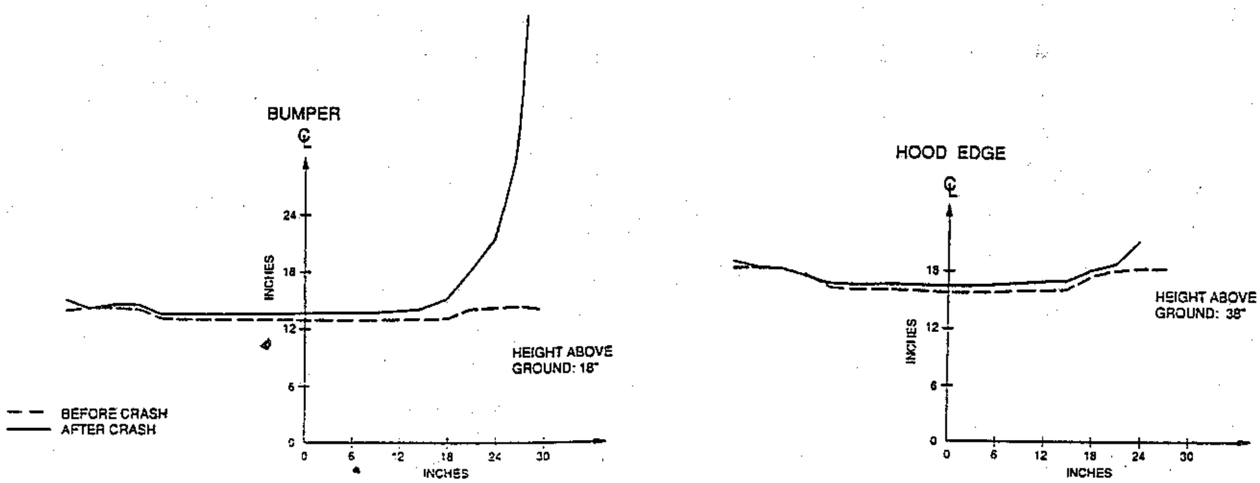


TABLE F5

TEST VEHICLE FRONT PROFILE - TEST 445

Car Side	Distance from C/L Inches.	Bumper, Inches (24" Above Ground)		Center of Grill Edge (24" Above Ground)		Hood Edge, Inches (30" Above Ground)	
		Before Crash	After Crash	Before Crash	After Crash	Before Crash	After Crash
Right	39	25 3/4	-	-	-	-	-
	36	19 1/2	-	26	25 3/4	-	-
	34	-	26 1/2	-	-	-	-
	33	15 5/8	-	20 3/4	22 3/4	26 3/8	20 1/2
	30	15 3/8	15 3/4	20 5/8	23 1/4	26 1/4	20 1/4
	27	15 1/8	15 1/4	20 3/4	23 1/2	26 1/4	20 1/8
	24	15	15 3/8	20 5/8	22 1/2	26	20
	21	15	15 1/4	20 3/4	21 3/4	25 7/8	19 7/8
	18	14 7/8	15	19 7/8	20 1/2	25 3/4	19 5/8
	15	14 3/8	14 1/2	19 5/8	19 5/8	25 1/4	18 7/8
	12	14	14	19	19	25 1/8	18 1/2
	9	13 3/8	13 1/2	18 3/8	18 3/8	24 5/8	17 7/8
	6	13 3/4	12 7/8	17 7/8	17 1/2	24 3/8	17 1/4
	3	12 3/8	12 3/8	17 5/16	16 3/4	23 3/4	16 5/8
$\mathbb{C}_L$	0	11 7/8	12	17 3/8	16 7/8	23 1/2	16 1/8
Left	3	12 3/8	12	17 5/16	16 3/4	23 3/4	16 5/8
	6	12 3/4	12 1/2	17 7/8	17 3/8	24 3/8	17
	9	13 3/8	11 5/8	18 3/8	17 5/8	24 5/8	17 3/8
	12	14	13 3/4	19	18 1/4	25 1/8	17 7/8
	15	14 3/8	13 7/8	19 5/8	18 3/4	25 1/4	18 1/4
	18	14 7/8	14 1/4	19 7/8	19 1/4	25 3/4	18 1/2
	21	15	14 5/8	20 3/4	-	25 7/8	18 1/2
	24	15	14 3/4	20 5/8	23 1/2	26	18 1/2
	27	15 1/8	15 3/8	20 3/4	23 3/4	26 1/4	18 3/8
	30	15 3/8	17 1/8	20 5/8	-	26 1/4	18 3/8
	33	15 5/8	28 1/2	20 5/8	-	26 3/8	18 3/8
	36	19 1/2	-	20 3/4	-	-	-
	39	25 3/4	-	26	-	-	-

FIGURE F5

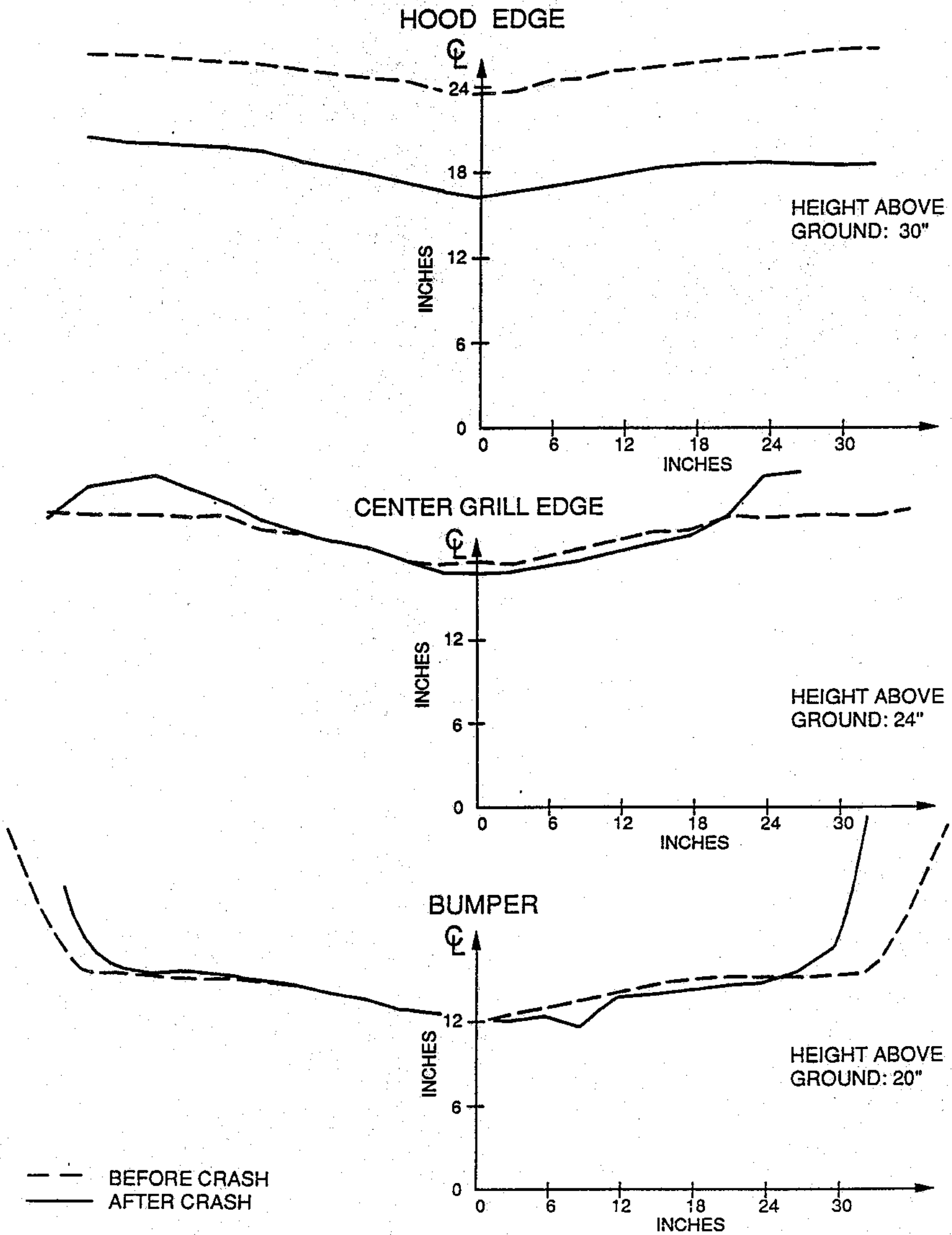

HOOD EDGE
℄
24
18
12
6
0
INCHES
HEIGHT ABOVE GROUND: 30"
0 6 12 18 24 30
INCHES
CENTER GRILL EDGE
℄
12
6
0
INCHES
HEIGHT ABOVE GROUND: 24"
0 6 12 18 24 30
INCHES
BUMPER
℄
12
6
0
INCHES
HEIGHT ABOVE GROUND: 20"
BEFORE CRASH
AFTER CRASH
0 6 12 18 24 30
INCHES

TABLE F6

TEST VEHICLE FRONT PROFILE - TEST 446

Car Side	Distance from C/L Inches.	Bumper, Inches (18" Above Ground*)		Hood Edge Inches (28" Above Ground)	
		Before Crash	After Crash	Before Crash	After Crash
Right	39	-	24 1/2	-	-
	36	-	16 5/8	-	-
	33	-	16 1/4	-	
	30	15	15 3/4	-	-
	27	14 1/4	15 3/8	21 1/2	-
	24	13 7/8	15	19 5/8	21 1/2
	21	13 5/8	14 1/2	19 3/8	20 7/8
	18	13 3/8	14 1/4	19	20 1/8
	15	13 1/4	14	18 7/8	20 1/8
	12	13 1/8	13 3/4	18 3/4	19 3/8
	9	13	13 1/2	18 1/2	19 1/4
	6	13	13 1/2	18 1/2	21 3/8
	3	13	13 1/4	18 1/2	21 3/8
C/L	0	12 7/8	13 3/8	18 5/8	21 5/8
Left	3	13	13 1/8	18 1/2	21 3/4
	6	13	13 1/8	18 1/2	22 1/4
	9	13	13 1/4	18 1/2	22 1/2
	12	13 1/8	13 1/4	18 3/4	22 7/8
	15	13 1/4	13 3/8	18 7/8	23 1/2
	18	13 3/8	13 1/2	19	24 1/4
	21	13 5/8	13 7/8	19 3/8	24 3/4
	24	13 7/8	18	19 5/8	-
	27	14 1/4	-	21 1/2	-
	30	15	-	-	-

* Height above ground before test. After test, the bumper was inclined; the measurements were done horizontally.

FIGURE F6

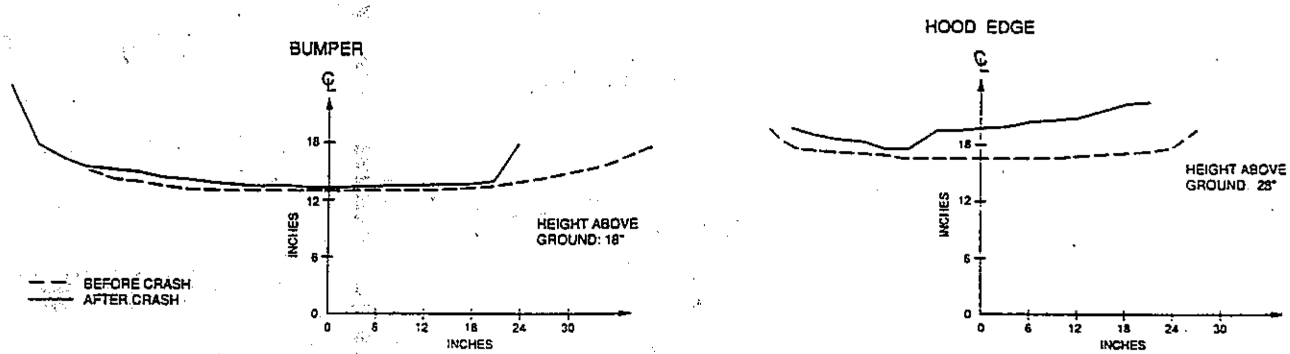


TABLE F7

BARRIER JOINT LATERAL DISPLACEMENTS - TESTS 441 AND 442

JOINT #	Test 441 DISPLACEMENT, INCHES	JOINT #	Test 442 DISPLACEMENT, INCHES
1	1.250	1	0.000
2	0.939	2	0.625
3	-0.625	3	1.000
4	0.000	4	-2.625
5	-0.250	5	-1.063
6	0.875	6	0.688
7	0.750	7	3.250
8	-0.063	8	7.125
9	3.000	9	11.125
10	6.250	10	17.250
11	11.750	11	25.875
12	18.625	12	19.250
13	26.125	13	44.375
14	32.375	14	51.750
15	41.500	15	54.750
16	49.250	16	54.500
17	57.250	17	53.250
18	64.000	18	42.000
19	68.188	19	22.625
20	69.125	20	9.937
21	65.375	21	1.063
22	60.000	22	0.125
23	48.750	23	-0.375
24	22.188	24	0.250
25	4.750	25	0.000
26	-0.750	26	0.000
27	-0.500	27	0.000
28	0.000	28	0.000
29	0.000	29	0.000
30	0.000	30	0.000
31	0.000	31	0.000
32	0.000	32	0.000
33	0.000	33	0.000
34	0.000	34	0.000
35	0.000	35	0.000
36	0.000	36	0.000
37	0.000	37	0.000
38	0.000	38	0.000
39	0.000	39	0.750
40	0.000	40	23.750

TABLE F8.

TABLE F8
BARRIER LONGITUDINAL DISPLACEMENTS - TEST 442

Segment No.	Upstream End Displacement, inches		Downstream End Displacement, inches	
	Segment Face	Segment Back	Segment Face	Segment Back
1	9 1/8	8 3/4	8 5/8	8 1/4
2	10	9	8 7/8	9 1/4
3	9 3/4	9 1/2	10	9 1/2
4	9 1/4	11	9 1/8	11 1/4
5	10 1/2	10	10 7/8	10 1/2
6	11 1/2	10	11	10 1/8
7	11 7/8	10	11 1/2	9 3/8
8	12 3/8	10 1/4	11 3/4	11 3/8
9	13 3/4	11 7/8	13	11 7/8
10	14 1/2	12 1/2	13 3/4	11 5/8
11	14	12 1/8	13 1/8	11 1/8
12	15 3/8	12 5/8	13 3/8	11 5/8
13	16 3/4	13 5/8	12 1/2	10 3/8
14	15 1/4	12 7/8	20 5/8	18 1/4
15	17 3/4	14 1/2	14 1/2	12 1/8
16	13 1/4	8 3/8	9 3/4	11 1/4
17	15 7/8	9 1/4	16 1/2	13 1/8
18	12 1/4	7 7/8	2 1/8	2 3/8
19	1/2	3/8	-2 7/8	2 1/4
20	-2 9/16	2 1/2	-2 1/8	2 1/16
21	-2 1/4	2 1/4	-2 3/8	2 3/8
22	-3/8	1	0	5/8
23	0	5/8	0	9/16
24	0	3/8	0	0
25	-	-	-	-
26	-	-	-	-
27	-	-	-	-
28	-	-	-	-
29	-	-	-	-
30	-	-	-	-
31	-	-	-	-
32	-	-	-	-
33	-	-	-	-
34	-	-	-	-
35	-	-	-	-
36	-	-	-	-
37	-	-	-	5/8*
38	0	7/8*	1*	1*
39	4 3/8*	-3 7/8*	3 1/2*	14 1/8*
40	6 1/4*	5 1/2*	2 3/4*	17 1/2*

Barrier face indicates impact side.
Downstream displacement is considered positive. Upstream displacement is negative.
* Displacements due to a second car impact with the barrier.

TABLE F9
BARRIER JOINT LOCATION - TEST 443

	BEFORE		AFTER		
JOINT #	OFFSET	DISTANCE	OFFSET	DISTANCE	MOVE LAT
1	0	0	0.001	0.002	0
2	0.019	3.27	0.031	3.277	0.012
3	-0.012	6.528	-0.001	6.522	0.011
4	0.001	9.79	0.007	9.782	0.006
5	-0.054	13.043	-0.049	13.046	0
6	-0.051	16.302	-0.046	16.304	0
7	-0.066	19.574	-0.057	19.58	0.009
8	-0.024	22.846	-0.013	22.854	0.011
9	-0.047	26.111	-0.034	26.121	0.013
10	-0.033	29.376	-0.033	29.376	0
11	-0.041	32.633	-0.043	32.63	0
12	-0.065	35.9	-0.062	35.901	0
13	-0.086	39.185	-0.083	39.186	0
14	-0.082	42.453	-0.079	42.455	0
15	-0.093	45.726	-0.076	45.729	0.017
16	-0.117	48.981	-0.108	48.991	0.009
17	-0.132	52.272	-0.12	52.282	0.012
18	-0.14	55.536	-0.131	55.546	0.009
19	-0.136	58.832	-0.144	58.836	-0.008
20	-0.145	62.105	-0.13	62.12	0.015
21	-0.155	65.37	-.127	65.416	0.155
22	-0.16	68.622	-0.154	68.692	0.006
23	-0.148	71.896	-0.137	71.957	0.011
24	-0.128	75.153	-0.176	75.239	-0.048
25	-0.141	78.427	-0.116	78.512	0.025
26	-0.18	81.734	-0.171	81.815	0.009
27	-0.169	84.973	-0.191	85.101	-0.022
28	-0.184	88.236	-0.181	88.372	0
29	-0.173	91.537	-0.149	91.674	0.024
30	-0.17	94.789	-0.162	94.924	0.008
31	-0.156	98.068	-0.143	98.221	0.013
32	-0.139	101.327	-0.111	101.497	0.028
33	-0.129	104.596	-0.082	104.772	0.047
34	-0.078	107.871	-0.036	108.049	0.042
35	-0.043	111.13	-0.088	111.318	-0.045
36	-0.043	114.41	-0.059	114.606	-0.016
37	-0.029	117.676	-0.012	117.9	0.017
38	-0.053	120.949	-0.032	121.174	0.021
39	-0.012	124.23	-0.015	124.461	0
40	0.003	127.492	-0.028	127.734	-0.031
41	-0.014	130.766	-0.036	131.04	-0.022
42	-0.037	134.042	-0.017	134.322	0.02
43	-0.04	137.295	-0.005	137.606	0.035
44	-0.01	140.55	-0.036	140.862	-0.026
45	-0.018	143.836	-0.004	144.147	0.014
46	-0.048	147.082	-0.004	147.42	0.044
47	-0.038	150.367	-0.007	150.725	0.031
48	-0.08	153.637	-0.03	154.005	0.05
49	-0.06	156.898	-0.035	157.282	0.025
50	-0.02	160.171	-0.021	160.572	0

TABLE F9 (Continued)
BARRIER JOINT LOCATION - TEST 443

	BEFORE		AFTER		
JOINT #	OFFSET	DISTANCE	OFFSET	DISTANCE	MOVE LAT
51	-0.051	163.448	-0.027	163.858	0.024
52	-0.014	166.701	-0.018	167.137	0
53	0	169.994	-0.014	170.417	-0.014
54	0.001	173.242	0.233	173.699	0.232
55	-0.016	176.522	0.532	176.961	0.548
56	0.01	179.798	0.838	180.227	0.828
57	-0.008	183.068	1.426	183.454	1.434
58	0.003	186.336	1.888	186.709	1.885
59	0.015	189.607	2.241	189.973	2.226
60	0.06	192.89	2.509	193.261	2.449
61	0.055	196.153	2.799	196.511	2.744
62	0.038	199.422	3.108	199.79	3.07
63	0.008	202.717	3.443	203.067	3.435
64	0.039	205.979	3.597	206.347	3.558
65	0.036	209.279	3.7	209.642	3.664
66	-0.01	212.539	3.731	212.927	3.741
67	0.049	215.799	3.626	216.198	3.577
68	0.02	219.077	3.52	219.462	3.5
69	0.063	222.33	3.438	222.746	3.375
70	0.027	225.61	3.3	226.021	3.273
71	0.038	228.892	3.202	229.302	3.164
72	0.006	232.162	3.134	232.588	3.128
73	-0.013	235.436	2.635	235.853	2.648
74	-0.019	238.701	1.333	238.823	1.352
75	-0.014	241.98	0.033	241.831	0.047
76	-0.036	245.242	-0.095	245.103	-0.059
77	-0.019	248.508	-0.023	248.374	0
78	-0.032	251.796	-0.026	251.666	0.006
79	-0.065	255.092	-0.07	254.962	-0.005
80	-0.066	258.369	-0.079	258.247	-0.013
81	-0.088	261.647	-0.096	261.536	-0.008
82	-0.094	264.938	-0.074	264.804	0.02
83	-0.087	268.218	-0.085	268.114	0
84	-0.104	271.509	-0.082	271.39	0.022
85	-0.058	274.793	-0.094	274.695	-0.036
86	-0.096	278.06	-0.107	277.968	-0.011
87	-0.071	281.326	-0.086	281.238	-0.015
88	-0.057	284.597	-0.044	284.504	0.013
89	-0.062	287.881	-0.044	287.784	0.018
90	-0.047	291.139	0.025	291.053	0.072
91	-0.031	294.408	0.34	294.307	0.371
92	-0.022	297.672	0.966	297.533	0.988
93	0.012	300.947	1.384	300.787	1.372
94	0.003	304.208	2.098	303.971	2.095
95	0.005	307.476	2.367	307.213	2.362
96	0.004	310.74	1.835	310.436	1.831
97	0.004	313.999	1.919	313.709	1.915
98	0.002	317.277	0.897	316.821	0.895
99	0	320.528	-0.181	319.883	-0.181

TABLE F10
BARRIER JOINT LOCATION - TEST 444

	BEFORE		AFTER	
JOINT #	OFFSET	DISTANCE	OFFSET	DISTANCE
1	0	0	0.007	-0.007
2	-0.118	3.272	-0.122	3.268
3	-0.109	6.552	-0.113	6.548
4	-0.18	9.802	-0.18	9.801
5	-0.07	13.074	-0.078	13.081
6	-0.062	16.361	-0.063	16.361
7	-0.062	19.603	-0.056	19.609
8	-0.039	22.905	-0.044	22.9
9	-0.086	26.153	-0.068	26.163
10	-0.065	29.442	-0.068	29.437
11	-0.05	32.722	-0.053	32.719
12	0.021	35.971	0.029	35.989
13	-0.015	39.255	-0.025	39.237
14	-0.087	42.513	-0.076	42.514
15	-0.114	45.783	-0.118	45.776
16	-0.137	49.032	-0.141	49.027
17	-0.139	52.319	-0.129	52.316
18	-0.184	55.568	-0.183	55.569
19	-0.121	58.822	-0.127	58.836
20	-0.085	62.111	-0.087	62.106
21	-0.042	65.39	-0.041	65.393
22	-0.084	68.62	-0.071	68.635
23	-0.098	71.897	-0.101	71.887
24	-0.135	75.144	-0.134	75.15
25	-0.135	78.419	-0.135	78.424
26	-0.118	81.682	-0.119	81.672
27	-0.182	84.93	-0.182	84.926
28	-0.117	88.176	-0.127	88.186
29	-0.164	91.449	-0.164	91.441
30	-0.213	94.722	-0.214	94.719
31	-0.156	98.007	-0.155	97.995
32	-0.146	101.267	-0.146	101.263
33	-0.175	104.535	-0.182	104.563
34	-0.109	107.803	-0.103	107.817
35	-0.082	111.093	-0.098	111.115
36	-0.142	114.358	-0.137	114.376
37	-0.165	117.643	-0.145	117.676
38	-0.175	120.911	-0.189	120.943
39	-0.165	124.18	-0.172	124.222
40	-0.158	127.468	-0.164	127.526
41	-0.213	130.735	-0.191	130.803
42	-0.178	134.006	-0.179	134.092
43	-0.161	137.282	-0.181	137.376
44	-0.21	140.55	-0.212	140.631
45	-0.178	143.827	-0.156	143.921
46	-0.16	147.102	-0.005	147.21
47	-0.122	150.353	0.328	150.462
48	-0.133	153.643	0.737	153.72
49	-0.133	156.901	1.139	156.954
50	-0.124	160.181	1.489	160.239

TABLE F10 (Continued)
BARRIER JOINT LOCATION - TEST 444

	BEFORE		AFTER	
JOINT #	OFFSET	DISTANCE	OFFSET	DISTANCE
51	-0.128	163.452	1.638	163.503
52	-0.106	166.721	1.415	166.767
53	-0.108	169.987	1.202	170.039
54	-0.054	173.258	0.301	173.181
55	-0.067	176.519	-0.049	176.432
56	-0.048	179.816	-0.027	179.741
57	-0.094	183.078	-0.08	183.012
58	-0.102	186.337	-0.1	186.268
59	-0.073	189.62	-0.082	189.548
60	-0.054	192.895	-0.068	192.828
61	-0.082	196.181	-0.029	196.126
62	-0.085	199.447	-0.103	199.409
63	-0.025	202.716	-0.05	202.671
64	-0.083	206.015	-0.079	205.975
65	-0.064	209.264	-0.067	209.253
66	-0.063	212.532	-0.07	212.537
67	-0.067	215.825	-0.055	215.816
68	-0.035	219.102	-0.058	219.106
69	-0.046	222.372	-0.071	222.388
70	-0.058	225.667	-0.062	225.658
71	-0.04	228.933	-0.05	228.938
72	0.009	232.205	0.001	232.209
73	0.029	235.488	0.018	235.483
74	0.027	238.776	0.029	238.765
75	0.003	242.037	0	242.04
76	0.059	245.305	0.067	245.312
77	0.031	248.593	0.027	248.583
78	0.026	251.886	0.033	251.871
79	0.025	255.128	0.014	255.134
80	0.021	258.405	0.017	258.406
81	-0.04	261.697	-0.03	261.692
82	-0.035	264.965	-0.033	264.963
83	-0.013	268.246	-0.026	268.252
84	0.033	271.528	0.019	271.523
85	-0.01	274.807	-0.006	274.805
86	0.037	278.079	0.036	278.08
87	0.002	281.346	0.003	281.345
88	-0.001	284.6	-0.021	284.608
89	0.008	287.883	0.009	287.872
90	0.018	291.146	0.023	291.134
91	-0.013	294.408	-0.028	294.404
92	-0.032	297.679	-0.051	297.676
93	-0.019	300.929	-0.02	300.929
94	-0.022	304.188	-0.026	304.19
95	-0.057	307.454	-0.048	307.452
96	-0.046	310.739	-0.04	310.726
97	-0.05	314.012	-0.044	314.009
98	-0.06	317.269	-0.044	317.264
99	0	320.517	0.011	320.522

TABLE F11
BARRIER JOINT LOCATION - TEST 445

	BEFORE		AFTER	
JOINT #	OFFSET	DISTANCE	OFFSET	DISTANCE
1	0.000	0.000	-0.005	0.038
2	-0.119	3.271	-0.120	3.313
3	-0.118	6.541	-0.120	6.585
4	-0.166	9.801	-0.162	9.850
5	-0.070	13.072	-0.074	13.114
6	-0.058	16.363	-0.060	16.408
7	-0.041	19.608	-0.052	19.660
8	-0.045	22.892	-0.048	22.939
9	-0.071	26.150	-0.073	26.201
10	-0.051	29.435	-0.065	29.486
11	-0.049	32.714	-0.053	32.764
12	-0.037	35.987	0.028	36.031
13	-0.007	39.254	-0.020	39.293
14	-0.064	42.519	-0.073	42.566
15	-0.093	45.782	-0.114	45.832
16	-0.111	49.044	-0.127	49.083
17	-0.113	52.326	-0.127	52.371
18	-0.167	55.578	-0.185	55.618
19	-0.097	58.851	-0.114	58.897
20	-0.066	62.120	-0.086	62.161
21	-0.015	65.392	-0.045	65.437
22	-0.050	68.646	-0.072	68.690
23	-0.068	71.902	-0.091	71.947
24	-0.112	75.164	-0.135	75.207
25	-0.121	78.437	-0.136	78.488
26	-0.092	81.703	-0.119	81.765
27	-0.135	84.978	-0.154	85.038
28	-0.110	88.250	-0.170	88.319
29	-0.169	91.533	-0.172	91.609
30	-0.130	94.812	-0.155	94.875
31	-0.155	98.090	-0.183	98.160
32	-0.238	101.358	-0.240	101.438
33	-0.240	104.633	-0.287	104.712
34	-0.210	107.911	-0.199	107.996
35	-0.101	111.198	-0.180	111.296
36	-0.087	114.483	-0.118	114.583
37	-0.116	117.750	-0.149	117.847
38	-0.128	121.043	-0.177	121.144
39	-0.167	124.324	-0.209	124.424
40	-0.146	127.620	-0.220	127.734
41	-0.255	130.879	-0.273	131.005
42	-0.283	134.157	-0.314	134.299
43	-0.276	137.422	-0.301	137.565
44	-0.229	140.699	-0.273	140.848
45	-0.199	143.954	-0.219	144.132
46	-0.145	147.193	-0.133	147.421
47	-0.074	150.430	0.169	150.675
48	-0.129	153.681	0.555	153.937
49	-0.138	156.933	0.799	157.217
50	-0.096	160.190	1.015	160.495

TABLE F11 (Continued)
BARRIER JOINT LOCATION - TEST 445

	BEFORE		AFTER	
JOINT #	OFFSET	DISTANCE	OFFSET	DISTANCE
51	-0.147	163.442	1.378	163.757
52	-0.112	166.710	1.744	167.026
53	-0.088	169.980	2.035	170.302
54	-0.018	173.256	2.200	173.566
55	-0.028	176.525	2.380	176.854
56	0.001	179.816	2.582	180.153
57	-0.046	183.079	2.674	183.424
58	-0.026	186.327	2.809	186.687
59	-0.023	189.636	2.831	189.968
60	0.008	192.903	2.857	193.252
61	-0.025	196.194	2.759	196.545
62	-0.063	199.475	2.473	199.817
63	-0.029	202.752	1.833	203.039
64	-0.051	206.050	0.490	206.010
65	-0.047	209.322	-0.074	209.218
66	-0.041	212.587	-0.081	212.493
67	-0.035	215.885	-0.078	215.781
68	-0.012	219.170	-0.119	219.072
69	-0.034	222.446	-0.074	222.354
70	-0.029	225.731	-0.048	225.624
71	-0.016	228.999	-0.026	228.911
72	0.031	232.274	-0.043	232.190
73	0.044	235.561	0.010	235.476
74	0.052	238.844	0.026	238.767
75	0.040	242.110	-0.042	242.030
76	0.086	245.372	0.014	245.321
77	0.049	248.653	0.029	248.607
78	0.046	251.945	-0.054	251.897
79	0.048	255.209	-0.018	255.175
80	0.045	258.474	-0.014	258.448
81	-0.008	261.762	-0.058	261.741
82	-0.008	265.032	-0.053	265.021
83	0.005	268.319	-0.049	268.300
84	0.046	271.603	-0.008	271.584
85	0.011	274.878	-0.035	274.877
86	0.042	278.158	0.004	278.142
87	0.017	281.420	-0.024	281.406
88	-0.007	284.683	-0.047	284.679
89	0.030	287.954	-0.012	287.939
90	0.040	291.229	-0.004	291.915
91	-0.016	294.479	-0.056	294.475
92	-0.033	297.760	-0.080	297.747
93	0.002	301.012	-0.051	301.001
94	-0.010	304.265	-0.052	304.261
95	-0.015	307.530	-0.064	307.517
96	-0.034	310.804	-0.076	310.810
97	-0.033	314.096	-0.081	314.083
98	-0.026	317.348	-0.078	317.336
99	0.001	320.599	-0.041	320.592

TABLE F12
BARRIER JOINT LOCATION - TEST 446

	BEFORE		AFTER		
JOINT #	OFFSET	DISTANCE	OFFSET	DISTANCE	MOVE LAT
1	0.000	0.000	-0.007	-0.043	-0.007
1	0.000	0.000	-0.007	-0.043	-0.007
2	-0.031	3.260	-0.061	3.224	-0.030
3	-0.054	6.549	-0.066	6.526	-0.012
4	-0.094	9.807	-0.088	9.786	0.006
5	-0.112	13.046	-0.129	13.031	-0.017
6	-0.150	16.347	-0.144	16.339	0.006
7	-0.150	19.608	-0.156	19.576	-0.006
8	0.000	0.000	0.000	0.000	0.000
9	-0.161	26.172	-0.138	26.166	0.023
10	-0.195	29.443	-0.193	29.418	0.002
11	-0.177	32.716	-0.156	32.695	0.021
12	-0.274	35.957	-0.266	35.936	0.008
13	-0.263	39.251	-0.261	39.224	0.002
14	-0.240	42.496	-0.219	42.490	0.021
15	-0.226	45.766	-0.225	45.752	0.001
16	-0.203	49.071	-0.188	49.042	0.015
17	-0.244	52.305	-0.243	52.324	0.001
18	-0.293	55.576	-0.252	55.618	0.041
19	-0.339	58.859	-0.348	58.846	-0.009
20	-0.379	62.140	-0.331	62.105	0.048
21	-0.277	65.369	-0.286	65.393	-0.009
22	-0.270	68.642	-0.263	68.632	0.007
23	-0.332	71.863	-0.302	71.898	0.030
24	-0.282	75.165	-0.301	75.173	-0.019
25	-0.282	78.448	-0.308	78.418	-0.026
26	-0.300	81.738	-0.327	81.752	-0.027
27	-0.352	84.998	-0.328	85.034	0.024
28	-0.396	88.289	-0.389	88.280	0.007
29	-0.440	91.575	-0.414	91.563	0.026
30	-0.414	94.857	-0.396	94.848	0.018
31	-0.419	98.117	-0.444	98.099	-0.025
32	-0.463	101.366	-0.462	101.376	0.001
33	-0.452	104.618	-0.433	104.674	0.019
34	-0.492	107.879	-0.510	107.899	-0.018
35	-0.468	111.194	-0.497	111.199	-0.029
36	-0.463	114.457	-0.434	114.460	0.029
37	-0.425	117.727	-0.435	117.769	-0.010
38	-0.493	121.004	-0.494	121.030	-0.001
39	-0.527	124.279	-0.479	124.314	0.048
40	-0.507	127.555	-0.513	127.610	-0.006
41	-0.513	130.730	-0.500	130.878	0.013
42	-0.531	134.082	-0.503	134.156	0.028
43	-0.514	137.363	-0.528	137.433	-0.014
44	-0.505	140.630	-0.462	140.710	0.043
45	-0.486	143.906	-0.466	143.983	0.020
46	-0.437	147.198	-0.449	147.303	-0.012
47	-0.456	150.469	-0.438	150.572	0.018
48	-0.353	153.755	-0.389	153.852	-0.036
49	-0.323	157.019	-0.362	157.168	-0.039
50	-0.341	160.290	-0.392	160.430	-0.051

TABLE F12 (Continued)
BARRIER JOINT LOCATION - TEST 446

	BEFORE		AFTER		
JOINT #	OFFSET	DISTANCE	OFFSET	DISTANCE	MOVE LAT
1	0.000	0.000	-0.007	-0.043	-0.007
51	-0.355	163.573	-0.359	163.723	-0.004
52	-0.352	166.856	0.062	166.987	0.414
53	-0.315	170.130	0.505	170.231	0.820
54	-0.250	173.418	0.854	173.523	1.104
55	-0.232	176.661	1.005	176.818	1.237
56	-0.164	179.935	1.488	180.024	1.652
57	-0.163	183.207	1.891	183.273	2.054
58	-0.118	186.495	2.119	186.552	2.237
59	-0.040	189.752	2.204	189.848	2.244
60	-0.112	193.026	2.032	193.153	2.144
61	-0.078	196.301	1.957	196.413	2.035
62	-0.055	199.569	1.392	199.675	1.447
63	-0.164	202.836	0.117	202.677	0.281
64	-0.081	206.116	-0.096	205.938	-0.015
65	-0.096	209.375	-0.116	209.223	-0.020
66	-0.090	212.653	-0.096	212.487	-0.006
67	-0.100	215.931	-0.111	215.774	-0.011
68	-0.087	219.188	-0.123	219.070	-0.036
69	-0.113	222.486	-0.116	222.338	-0.003
70	0.098	225.738	-0.152	225.612	-0.250
71	-0.110	229.037	-0.097	228.908	0.013
72	-0.133	232.317	0.131	232.185	0.264
73	-0.166	235.578	0.169	235.477	0.335
74	-0.137	238.856	-0.205	238.782	-0.068
75	-0.146	242.092	-0.222	242.036	-0.076
76	-0.202	245.368	-0.235	245.329	-0.033
77	-0.195	248.629	-0.225	248.588	-0.030
78	-0.207	251.924	-0.222	251.872	-0.015
79	-0.167	255.193	-0.195	255.138	-0.028
80	-0.160	258.472	-0.195	258.446	-0.035
81	-0.131	261.736	-0.151	261.725	-0.020
82	-0.125	264.995	-0.167	264.997	-0.042
83	-0.099	268.313	-0.174	268.253	-0.075
84	-0.126	271.503	-0.158	271.510	-0.032
85	-0.123	274.796	-0.141	274.771	-0.018
86	-0.127	278.051	-0.138	278.047	-0.011
87	-0.107	281.324	-0.094	281.327	0.013
88	-0.095	284.571	-0.130	284.590	-0.035
89	-0.071	287.842	-0.145	287.850	-0.074
90	-0.073	291.104	-0.089	291.077	-0.016
91	-0.073	294.383	-0.076	294.372	-0.003
92	-0.043	297.643	-0.080	297.617	-0.037
93	-0.052	300.935	-0.072	300.922	-0.020
94	-0.030	304.187	-0.061	304.202	-0.031
95	-0.021	307.456	-0.031	307.461	-0.010
96	0.001	310.706	-0.055	310.710	-0.056
97	0.019	313.985	-0.045	313.971	-0.064
98	-0.014	317.232	-0.061	317.242	-0.047
99	0.000	320.487	-0.037	320.493	-0.037

TABLE F13 - BARRIER JOINT MEASUREMENTS - TRANSFER VEHICLE DEMONSTRATION

Pass Number	MEASUREMENT LOCATION: Uphill End: Absolute length	Uphill End: Change in length, inches	Downhill End: Absolute length	Downhill End: Change in length, inches	Transfer Vehicle Movement Direction	Cycle Number	Measurement Condition
0	13' 0"	0	13' 0"	0	Reference Point	0	
1	12' 11 3/4"	-1/4	13' 11/16"	11/16	Downhill	I	Freestanding Barrier
2	12' 10 15/16"	-1 1/16	13' 13/16"	1 3/16	Downhill	I	
3	13' 1"	1	12' 11 7/16"	-5/16	Uphill	I	
4	12' 11 3/4"	- 1/4	12' 11 7/8"	- 1/8	Uphill	I	
5	12' 11 1/4"	-3/4	13' 1"	+1	Downhill	II	
6	12' 10 3/4"	-1 1/4	13' 1 3/8"	1 3/8	Downhill	II	
7	12' 11 1/2"	-1/2	13' 15/16"	15/16	Uphill	II	
8 *	12' 11 7/16"	-9/16	13' 0	0	Uphill	II	
9	12' 11 15/16"	1/2	13' 1"	1	Downhill	III	Barrier Tethered at Uphill End
10	12' 11 1/2"	1/16	13' 1 5/16"	1 5/16	Downhill	III	
11	12' 11 13/16"	3/8	13' 13/16"	13/16	Uphill	III	
12	12' 11 13/16"	3/8	13' 5/16"	5/16	Uphill	III	
13	13' 1/2"	1 1/16	13' 1 1/16"	1 1/16	Downhill	IV	
14	13' 1/16"	5/8	13' 1 1/16"	1 1/16	Downhill	IV	
15	13' 0"	9/16	13' 1 1/8"	1 1/8"	Uphill	IV	
16	13' 1/16"	5/8	13' 5/16"	5/16	Uphill	IV	

Measurements were taken to include 4 joints, after 15 joints from each end.

* This joint position is considered the reference points for the third and fourth cycle.

TABLE F14 - DISPLACEMENT OF DOWNHILL END OF MCB TRANSFER VEHICLE DEMONSTRATION

Pass #	Freestanding Segments		Pass #	Tethered Uphill End	
	Movement Direction	Downhill end Displacement, in		Movement Direction	Downhill end Displacement, in
1	Downhill	1 5/16	9	Downhill	1/8
2	Downhill	1 9/16	10	Downhill	3/4
3	Uphill	2 5/8	11	Uphill	1 1/4
4	Uphill	NA	12	Uphill	1 1/2
5	Downhill	2	13	Downhill	1 3/4
6	Downhill	3 1/8	14	Downhill	NA
7	Uphill	4 3/8	15	Uphill	2 1/2
8	Uphill	4 3/4	16	Uphill	3 5/8

FIGURE F7
PLOT OF SURVEY MEASUREMENTS - TEST 443

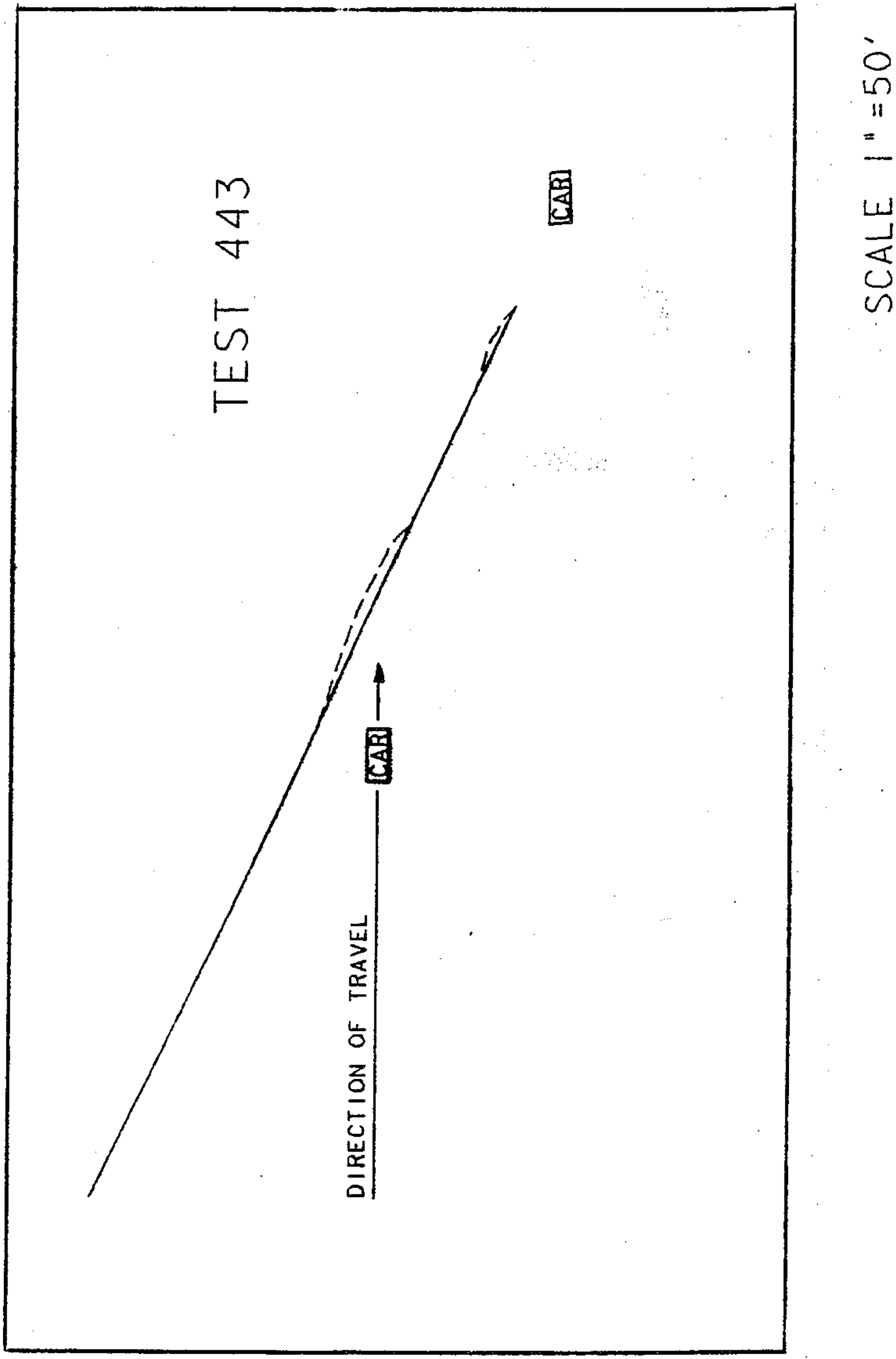


FIGURE F8
PLOT OF SURVEY MEASUREMENTS - TEST 444

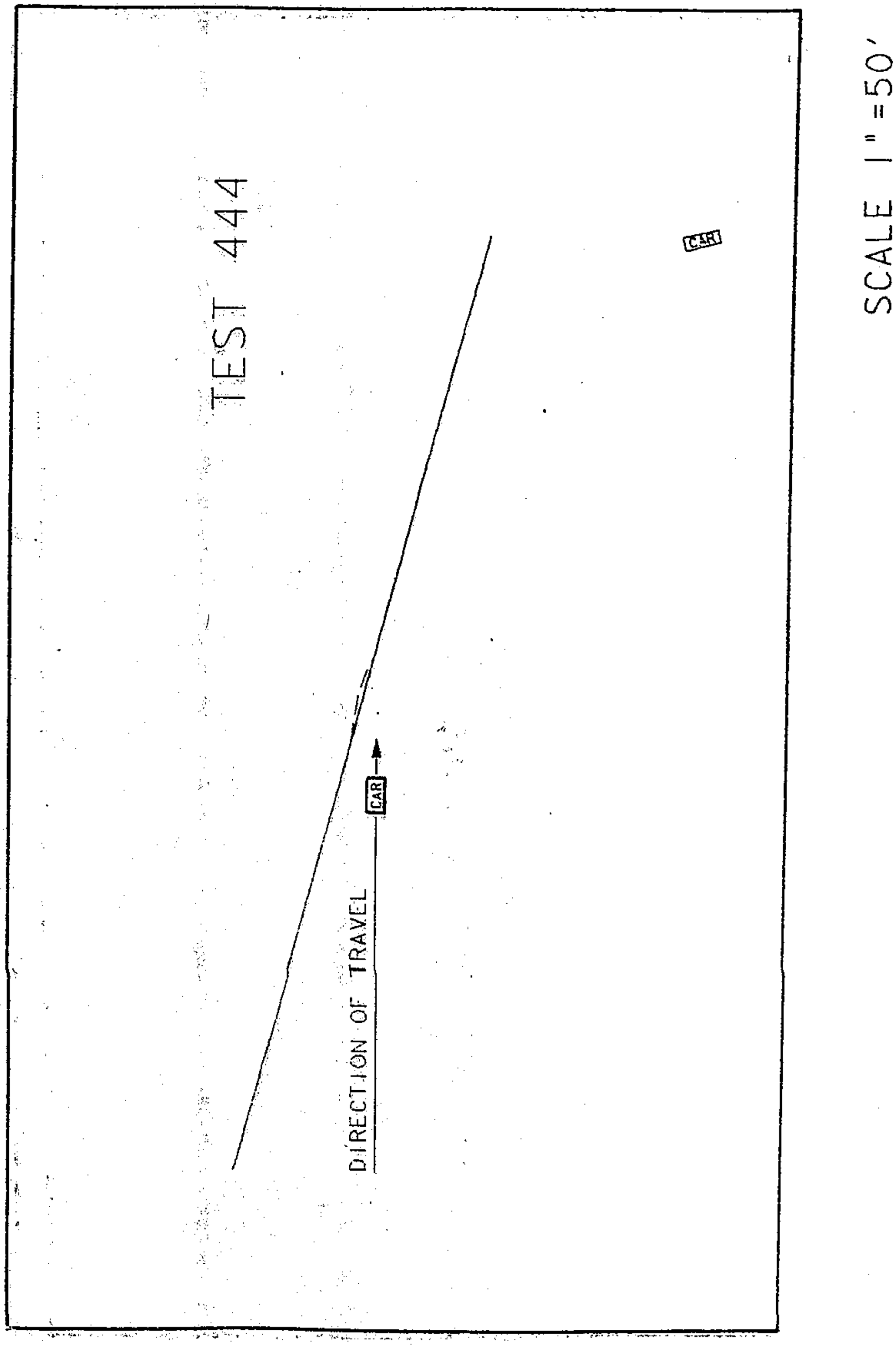


FIGURE F9
PLOT OF SURVEY MEASUREMENTS - TEST 445

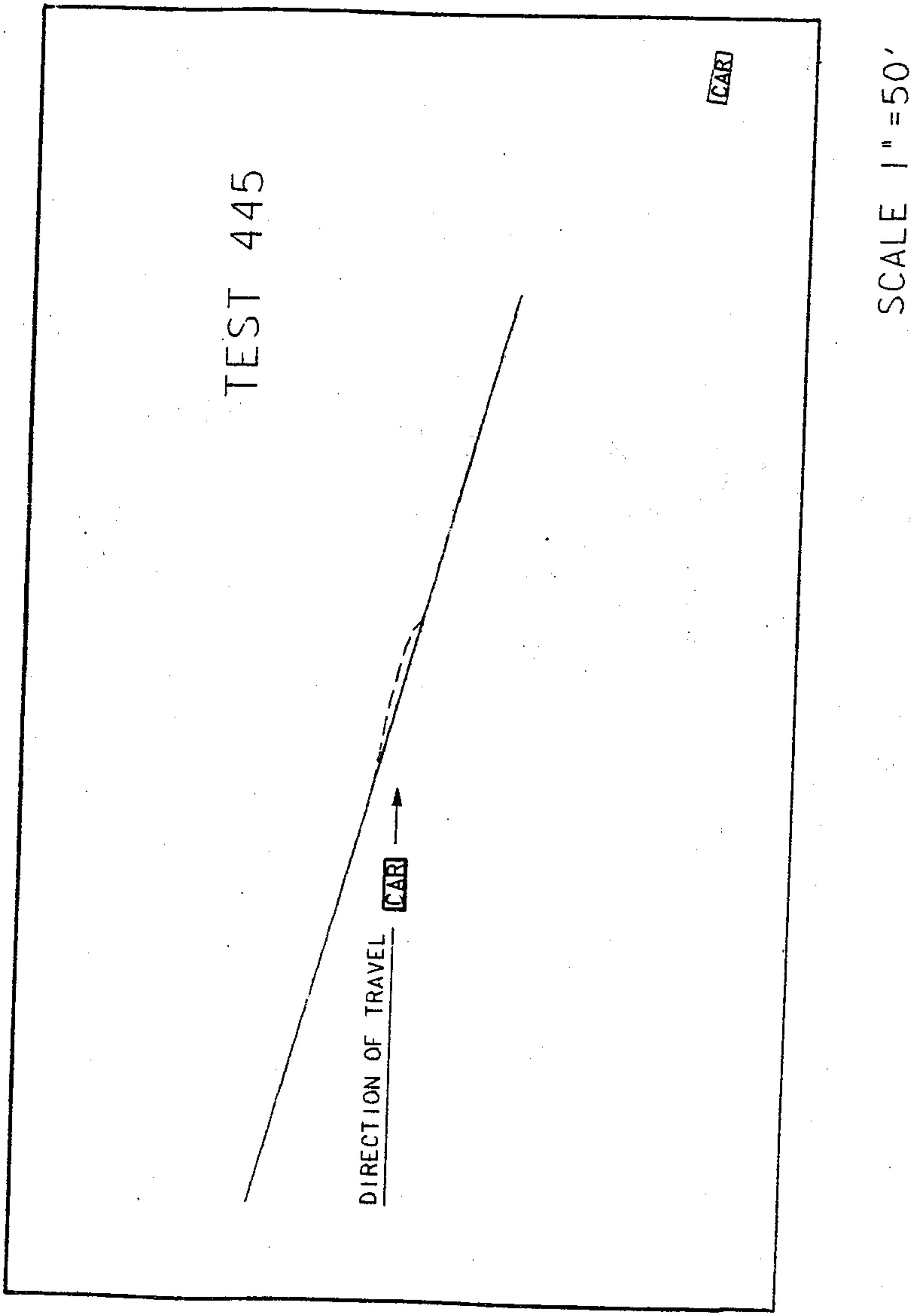
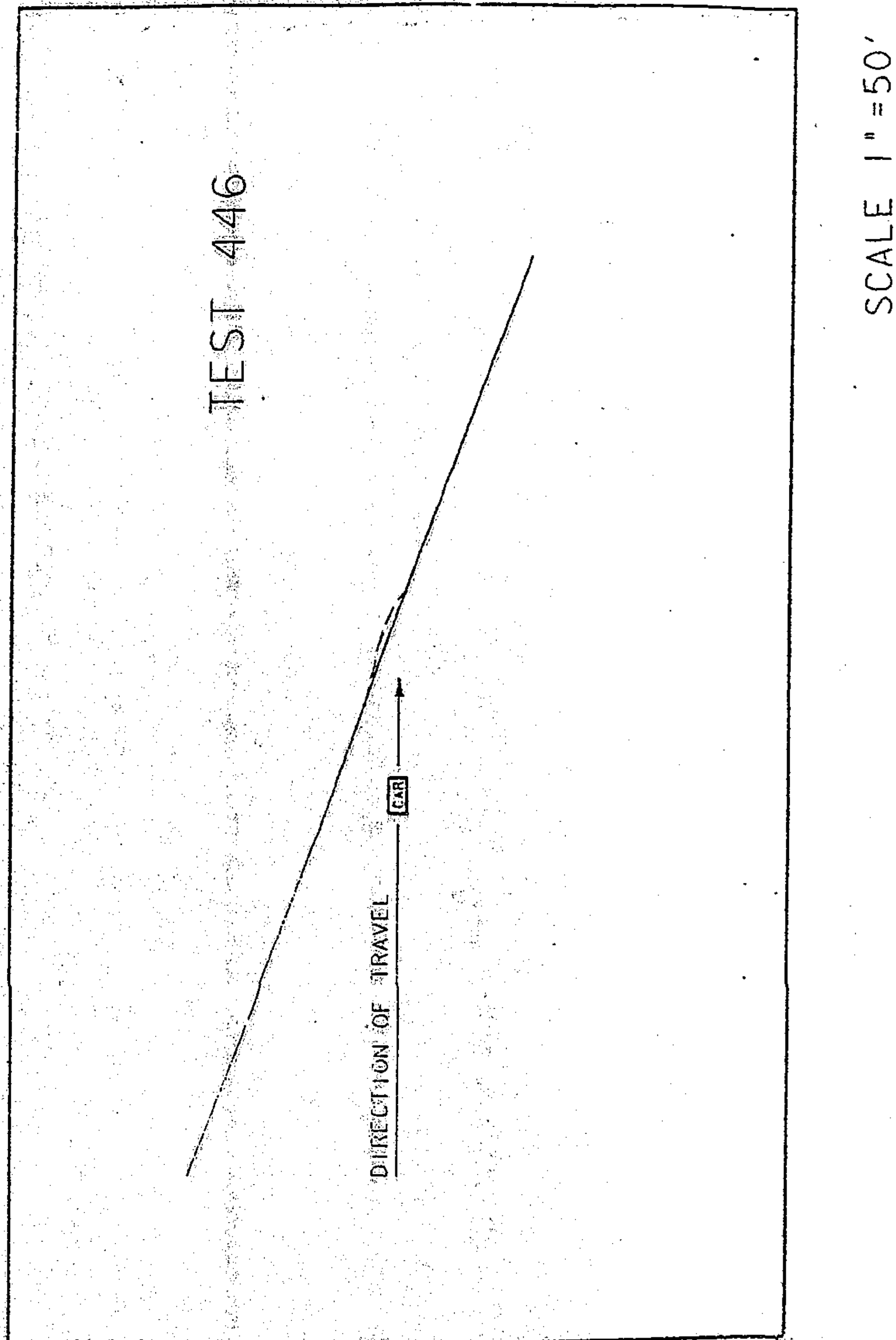


FIGURE F10
PLOT OF SURVEY MEASUREMENTS - TEST 446



Thirteen full scale crash tests were performed by Barrier Systems, Incorporated under the direction of Eric Nordlin to evaluate the safety performance of a movable concrete construction barrier. Results of that testing were presented at the 66th Annual Meeting of the Transportation Research Board, Washington D.C., January 12-15, 1987.

The barrier consisted of a chain of hinged, freestanding, one meter long (3.28 feet) reinforced concrete modules, 32 inches high with a modified configuration F shape as shown in Figures G1, G2, and G3. The movable construction barrier test results are presented in Table G1 and Figure G4. These tests generally followed NCHRP 230 guidelines, although instrumented dummies, accelerometers and high speed cameras were not used. Tables and Figures are from Reference 8.

FHWA reviewed the results of these tests and of the first test done by Caltrans (Test 441). On July 15, 1986, they approved the Barrier Systems Series 200 Movable Concrete Barrier for use as an experimental barrier in work zones, when specified by a state highway department.

FIGURE G1
CONCRETE MODULE USED IN BSI TESTS

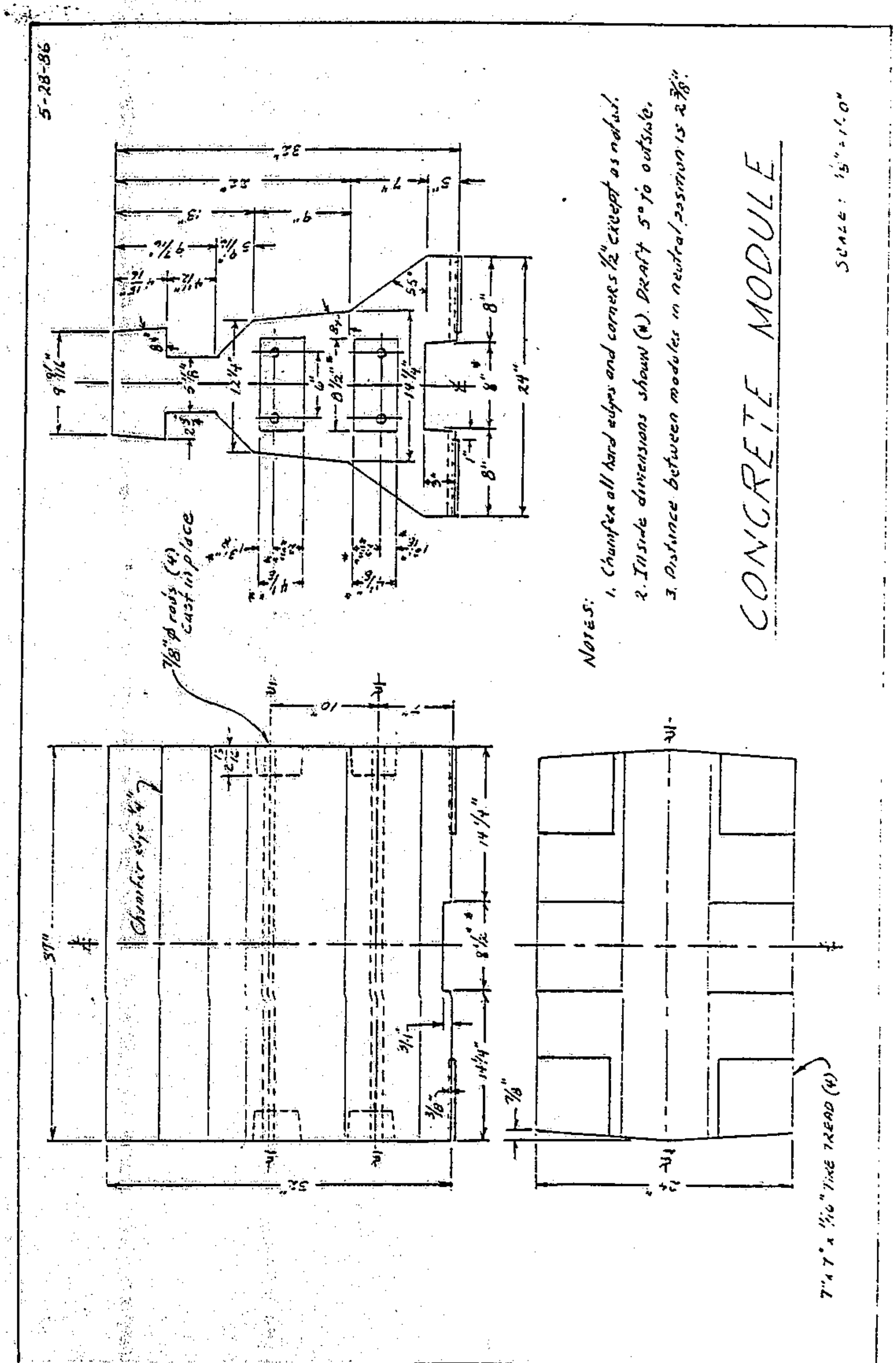


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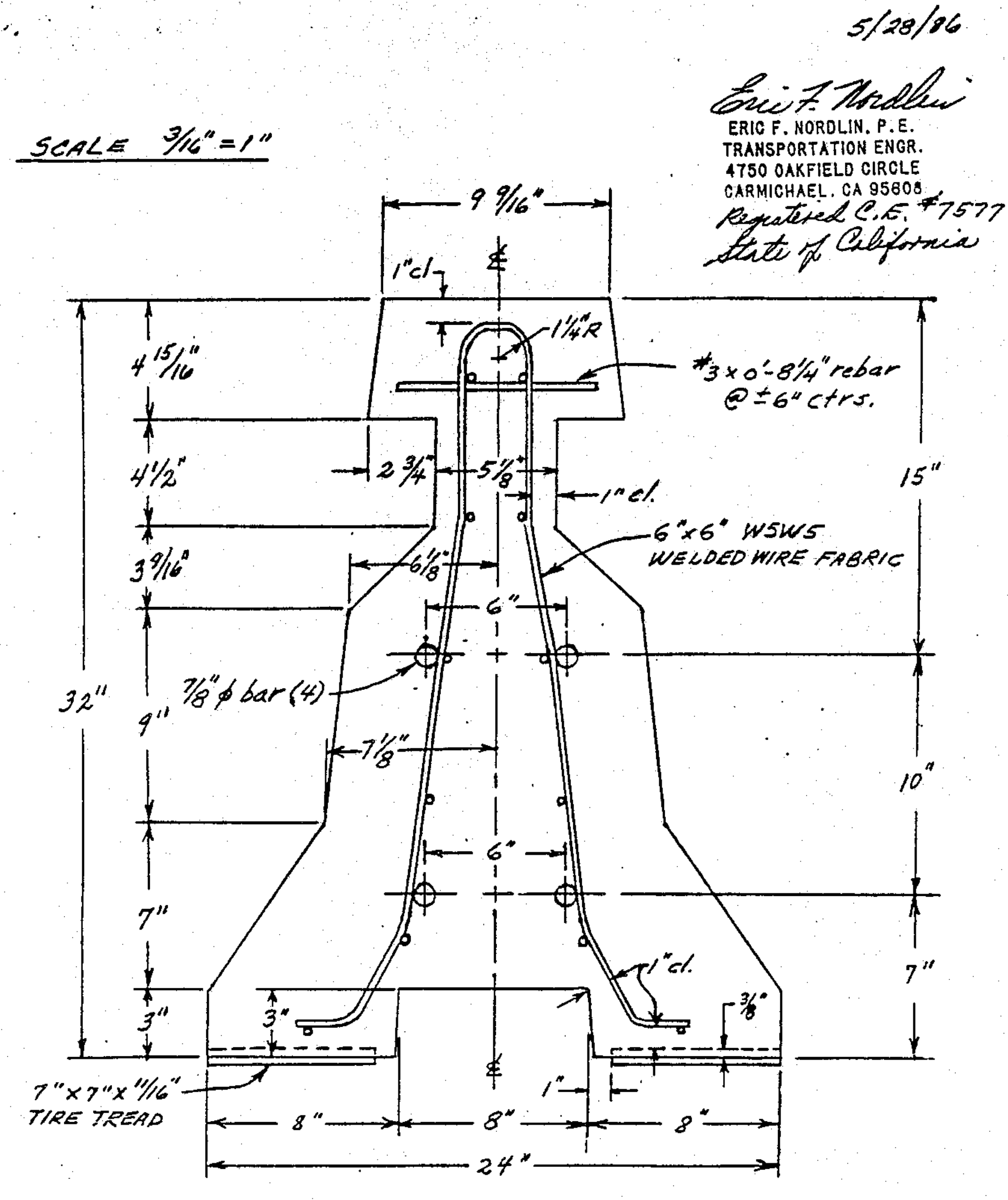
FIGURE G2
FORMER BSI BARRIER PROFILE AND REINFORCEMENT



REINFORCEMENT — WORK AREA BARRIER

FIGURE G3
LOWER HINGE ASSEMBLY OF FORMER BSI BARRIER

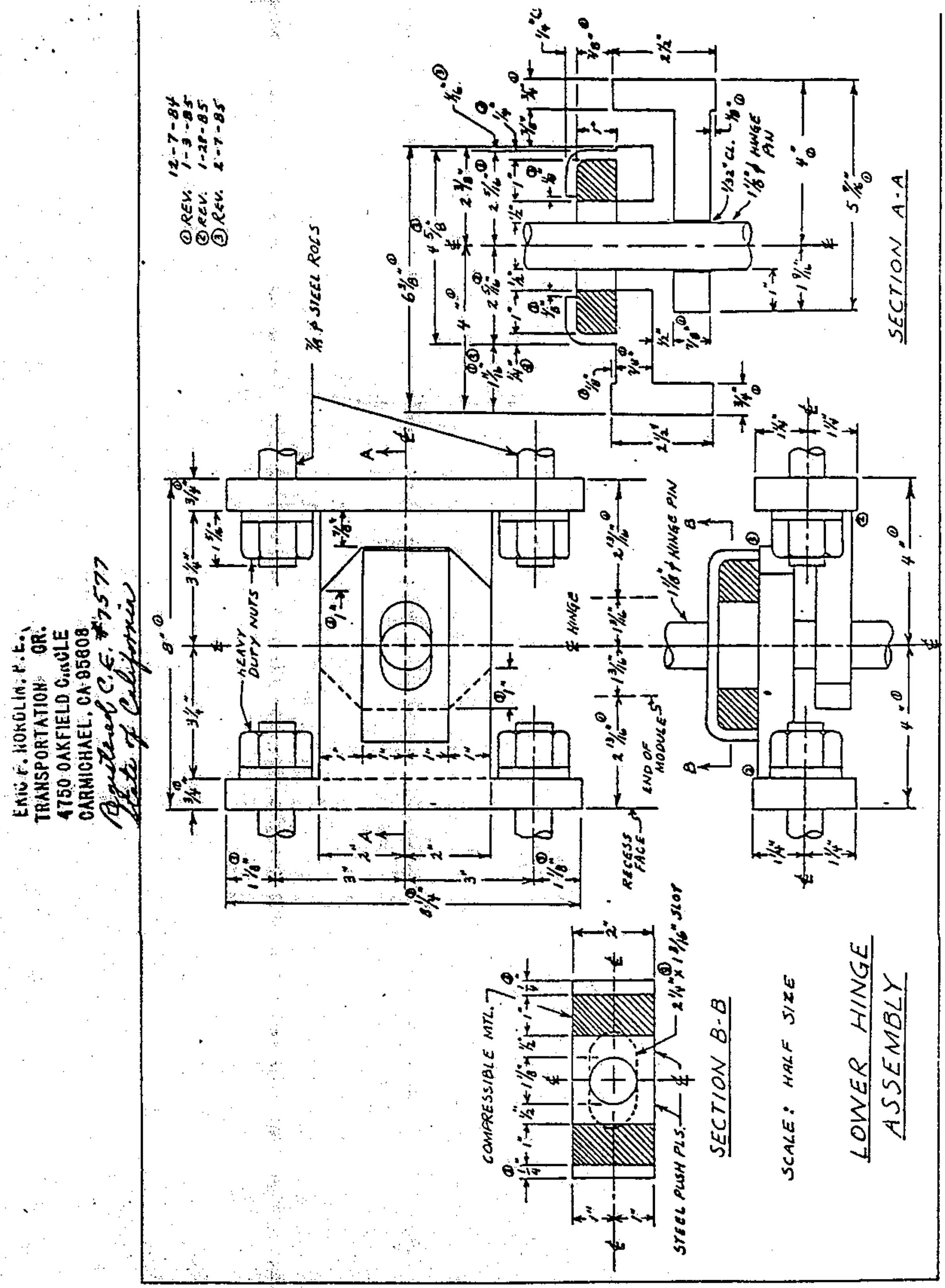


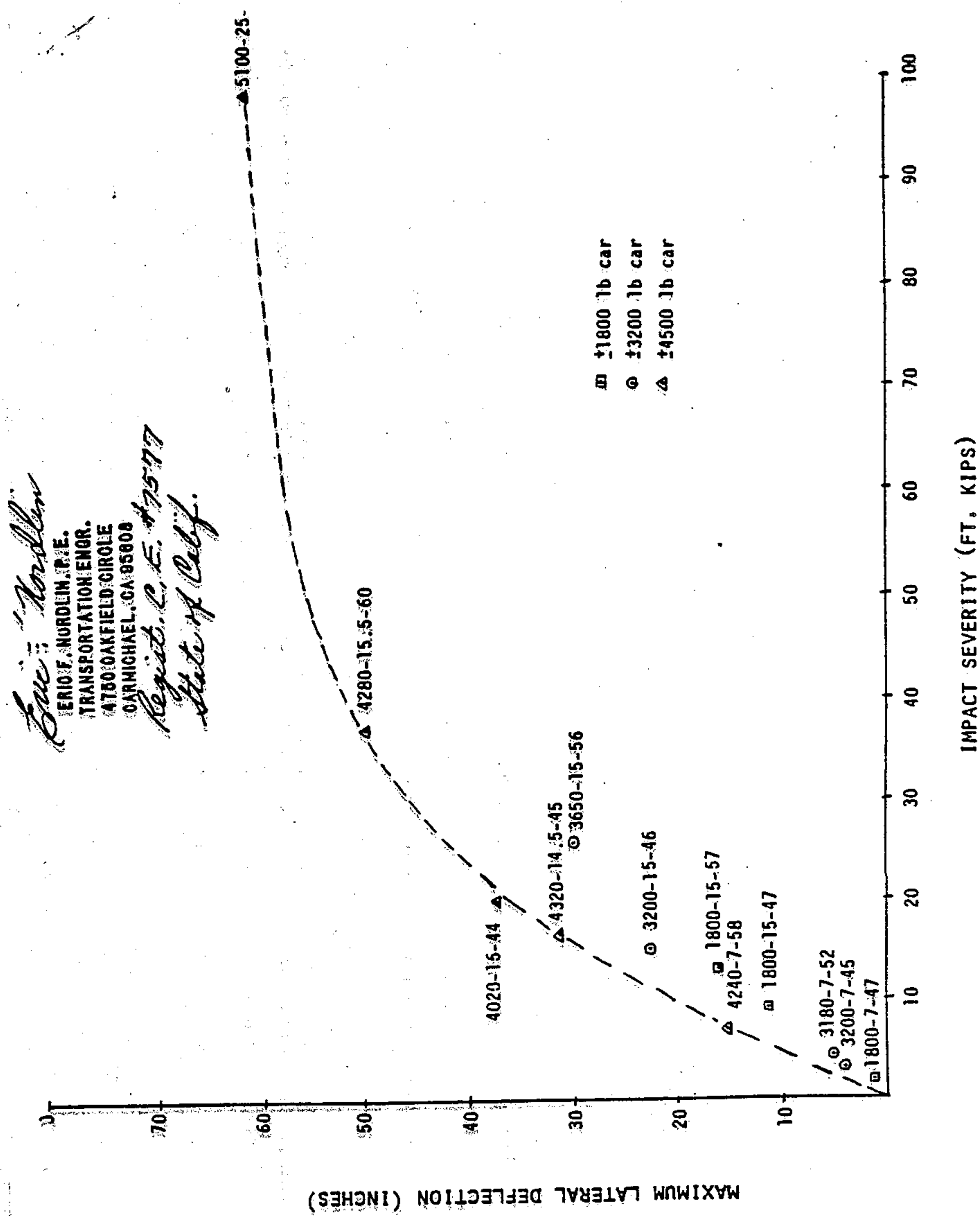
TABLE G1
BSI TEST RESULTS

ERIC F. NORDLIN

Table 1 - SUMMARY OF MOVABLE CONSTRUCTION BARRIER TEST RESULTS

TEST NO.	VEHICLE DESCRIPTION	VEHICLE WEIGHT (LB)	IMPACT ANGLE (DEGREE)	IMPACT SPEED (MPH)	IMPACT SEVERITY (FT-KIPS)	MAX. LATERAL BARRIER DE-FLECTION (IN)	EXIT ANGLE (DEGREES)	MAXIMUM DEPARTURE LFT WHEEL (FT)
022686-1	1972 Plymouth Scamp - 2 dr	3200	7	45	3	4-1/4	±2 30'	1/2
022786-1	1977 Honda Civic CVCC 2 dr	1800	7	47	2	1-1/4	±2	15
022886-1	1966 AMC. Station Wagon	3180	7	52	4	5-1/4	±1 30'	0
022886-2	1969 Ford Ranch Wagon	4240	7	58	7	15-3/8	±2 30'	1/2
030386-1	1977 Honda Civic CVCC 2 dr	1800	15	47	9	11-1/4	±8	45
030486-1	1972 Plymouth Scamp - 2 dr	3200	15	46	15	22-1/2	±6	2-1/2
030686-1	1977 Honda Civic CVCC 2 dr	1800	15	57	13	16	±4	4
030686-2	1974 Ford Gran Torino	4320	15	43	18	31-1/8	±8 30'	55
030686-3	1970 Plymouth Fury	3650	15	56	26	29-3/4	±4	1/2
031486-1	1961 Oldsmobile 88 Sedan	4280	15	60	35	49-3/8	±10	2-1/2
031986-1	1968 Cadillac Coupe de Ville	4850	25	50	73	Hinge Failed	N/A	0
032586-1	1971 Plymouth Fury	4020	15	44	17	37-1/2	0	0
032686-1	1969 Chrysler Station Wagon	5100	25	57	98	60-3/4	±15	16

FIGURE G4
BSI BARRIER TEST DATA



Movable concrete barriers have been installed or are being installed on seven projects in the United States for construction zone protection.

Four user states were surveyed on their operational experience with the MCB. The length, problems and observations of five installations are shown in Table H1. The survey was conducted by telephone.

Also shown on Table H1 is the experience reported on the operation of the Highway A-15 installation Northwest of Paris, France. The information in the table is extracted from reference 14. Information which is not available from that report is marked NA.

Conclusions:

The experience gained so far using MCB as a construction barrier has shown it is an effective highway traffic control device on roadways with a wide variety of geometries. The barrier has performed acceptably, preventing penetration into the work zone by vehicles with a wide range of sizes that have impacted it.

Although lateral deflections occur, up to 4 to 5 feet (1.2 to 1.5 m) in major accidents, no significant damage to the barrier has been reported.

The lack of adhesion of the rubber pads to the bottom of the barrier segments is a recurring failure. Further development on attaching the pads to the concrete barrier is needed.

TABLE H1: MCB OPERATIONAL EXPERIENCE

States Using Barrier(s)	Texas	Oklahoma	Pennsylvania	North Carolina 1	North Carolina 2	France
Barrier Quantity (supplied byBSI), ft (km)	6,751 (2.1)	14,602 (4.5)	34,810 (10.6)	8,000 (2.4)	19,000 (on both sides) (5.8)	7,900 (2.4 km)
Manufactured	8-87	3/88	6/88	10/87	10/88	8/86 (est)
Curvature (Radius, ft) (m)	5°(1,146) (349)	tangent	2.5°(2,292) (698)	tangent and curved	tangent and curved	tangent and curved (2133) (650)
Grades	None	None	NA	None	3%	1.5 - 2%
Longitudinal Creep	~1 ft over 800 ft	None	None	None	Noticeable	3.3 - 6.6 ft
Minor Impacts	numerous (not reported)	10-15 (not reported)	numerous (not reported)	numerous (not reported)	None	NA
Barrier Damage Due to Minor Impacts	Concrete Spalling	None	None	None	None	NA
Barrier Deflection Due to Minor Impacts	8-10 inches (0.2-0.25 m)	NA	less than 6 inches (0.15 m)	less than 1 ft (0.3 m)	-	NA
Vehicle Damage	Minor	Minor	Minor	Minor	-	NA
Major Impacts	Some	Some	One (involving a truck)	One (involving a tractor trailer)	One (hit and run)	NA
Barrier Damage Due to Major Impacts	Concrete Spalling	None	None	None	None	NA
Barrier Deflection Due to Major Impacts, ft (m)	2.5 - 3 (0.7-0.9)	1.5 - 2 (0.5-0.6)	NA	4-5 (1.2-1.5)	3 (0.9)	NA
Alignment Problems After Collisions	Yes. The barrier was not flexible enough to make a horizontal curve	None	None	None	None	NA
Straightening Method	Front end Loader	Front end Loader or Manual	Front end Loader	Available Const. Equipment	Available Const. Equipment	NA
Transfer Vehicle Use	Occasionally two operators needed	Twice daily for 2 months	Once	No leapfrogging was possible. Interfered with other lane traffic	Transfer vehicle requires too much time to change configuration	Twice daily
Transfer Vehicle Speed, mph (m/s)	NA	5-6 (2.2-2.7)	5-6 (2.2-2.7)	3 (1.3)	1-5 (0.4-2.2)	
Pad Problems	Yes 25% of pads were failing during barrier shifting.	None	Yes. Some pads came off during setting up of barrier.	Yes. Pad adhesive failed.	Yes. Pad adhesive failed.	NA
Compression or Stretch of Barrier	Yes. Compression of 1 ft over 800 ft after an accident	None	Yes. Compressed and stretched areas did not cause any problems	None	Compression caused "buckling" at joints	Yes. Compression

State of California | Business, Transportation and Housing Agency

Memorandum

To : Roger Stoughton/Sue Hawatky

Date : July 27, 1988

File No.:

From : DEPARTMENT OF TRANSPORTATION 739-5163
Office of Transportation Laboratory

Subject : LANE BARRIER TRANSPORTER

In early May you requested an evaluation of a lane barrier transporter and you gave me some technical characteristics of the transporter. To observe the carrier in operation, I watched a demonstration on May 3, 1988 at the Claude Wood Rock Plant in Lodi. During the demonstration I noted additional details about the carrier. This memo summarizes my evaluation, conclusions, and recommendations.

BACKGROUND

The primary concern is the heavy load carried by the two tires (one front and one rear) closest to the barrier "track" where you indicated that the expected load is 15,000 lbs--far exceeding the 4,500 lbs force exerted by a typical legal tire load. It is also much larger than a 9,000 lb super-single tire load. The tires that I saw at the demonstration were Firestone 12.00-20 rated at 105 psi maximum. The sidewalls showed 7,740 lbs @ 105 psi (cold). It appeared that the tire pressure was reduced so that the tires could carry double the load conditions shown on the sidewalls. The tire contact area was 9in x 16in (144 in^2) according to the measuring tape. No weight measurements were available during the demonstration. For my evaluation I used a tire load of 15,000 lbs distributed evenly over 144 in^2 (using a circle with 6.77in radius) and a contact pressure of 104 psi.

ANALYSIS

For preliminary study I used the ELSYM5 pavement model to predict tensile strain at the bottom of a lift of asphalt concrete (AC) pavement and compressive strain at the top of a lower layer. The model predicts the structural response of several layers of elastic material based on thickness, resilient modulus, and Poisson's ratio. The tensile strain is associated with cracking in the AC whereas the compressive strain is related to rutting of the section. After you informed me that the carrier will likely be used on construction sites and bridge decks, I decided to focus study on bridge decks where the AC lift can be quite thin (<3 in). To model a hypothetical worst case I used 2in of weak AC (150,000 psi modulus) over 6in of PCC (1,000,000 psi). In this case the compressive strain is not important so tensile strain is the only indicator for life of the system.

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RESULTS

Initial modeling results are very favorable. The model predicts 572 microstrain at the bottom of the AC. The number of cycles to failure are determined using fatigue curves from test roads and laboratory studies. Approximately 350,000 load cycles are tolerable by the pavement based on the predicted strain. If the carrier traverses the bridge twice each day of the year, the AC will crack in 479 years--well beyond the life of the structure!

Preliminary results may not accurately represent pavement response because of simplifying assumptions. For simplicity the model assumes that each layer is a homogeneous and isotropic material that behaves elastically. However, at slow speeds the AC is not elastic but is instead viscoelastic. Viscoelastic response varies with temperature--higher temperature promotes more extensive viscoelastic behavior. If the carrier is used at a site that typically has warm climate then the AC will behave much more viscoelastically under the carrier than the ELSYM5 model predicts. Strains will, therefore, be applied for longer periods than those on which the failure curves were derived. Effects from this increase are uncertain.

The loading used in the evaluation may poorly simulate actual load conditions. Research recently showed that radial tires carrying very heavy loads at high tire pressures exert pressure under the sidewalls that can be at least twice the pressure carried under the middle of the tire. This localized increase in contact pressure would be especially damaging for thin AC layers like those on bridge decks. I simulated a tire with doubly high contact pressures under the sidewall and predicted 608 microstrain at the bottom of the AC. Approximately 220,000 cycles are tolerable at the predicted tensile strain--still a predicted service of about 300 years, which is 37% less than initial results. This indicates how dramatically the predicted life is affected when the simplifications in the model are violated!

I believe the most important consequence of using the carrier on bridge decks can not be simulated using current models. Frequent pivoting, which is required to properly align the barriers, may cause the most damage--especially on hot bridge decks. The tensile and shear forces caused by short "jerky" turns can not be simulated by the ELSYM5 and are not the strain modes used in current failure curves. Pivoting will likely shorten the life substantially for AC layers located in hot climates. A quantitative prediction of effects from pivoting on service life is impossible without models and failure data. It is possible that pivoting could reduce the life of an AC lift to less than the typical life of an overlay.

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CONCLUSIONS/RECOMMENDATIONS

State-of-the-art models used in this analysis predict practically unlimited service life using the lane barrier transporter on bridge decks. However, the simplifying assumptions on which the model is based do not accurately represent load distribution in the contact area nor the viscoelastic behavior of the AC. More importantly, pivoting will greatly reduce predicted service life to a level that may be less than the life of a typical AC overlay. Quantitative predictions are impossible without further data and analysis. Pavement surface condition should be closely monitored where the carrier is used. Further analysis should be pursued if additional data become available.

Bill Nokes
Associate Materials & Research Engineer
Research, Enviro-Chemical Branch

BN;mgc